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ABSTRACT

A detailed examination of the nature and function of general aviation and a discussion of how the National Aeronautics and Space Administration (NASA) helps keep it on the cutting edge of technology are offered in this publication. The intricacies of aerodynamics, energy, and safety as well as the achievements in aeronautical experimentation are presented. Topic areas include: (1) what is general aviation; (2) aerodynamic efficiency; (3) internal combustion engines; (4) turbine engines; (5) commuter aviation; (6) general aviation utility; (7) safety improvements; (8) electronics and avionics; and (9) the future of general aviation. The field of general aviation is upheld as a dynamic and vital national asset to the United States economy and leadership potential. (ML)

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NASA and General Aviation

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FOREWORD

In 1915 a far-seeing United States Congress created the National Advisory Committee for Aeronautics (NACA). Its purpose: improve and develop American aviation, which was then in its infancy.

Today NACA's successor, the National Aeronautics and Space Administration (NASA), has a much broader mission. But as its name implies, NASA is still very much involved with aeronautics. Yet until now, the agency's important role in "general aviation" has never been fully told.

I find this rather astonishing, for in sheer numbers of planes, pilots, and air operations, general aviation is by far the largest single component of all U.S. aviation—civil and military.

NASA and General Aviation should do much to correct any possible misconception about the fine working relationship between the agency and the aircraft industry. Though perhaps not generally known, the industry continues to rely heavily on the basic technology that NASA and its predecessor have developed during decades of research. It is this traditional government-industry relationship that propelled America to a position of leadership in world aviation and space.

But as the author clearly points out, our leadership in some key technical areas is eroding. This is especially true in general aviation. While it is the biggest segment of the total aircraft industry, it still gets the smallest share of any federal funding budgeted for aerospace research.

Foreign nations, on the other hand, have different priorities. Several of them are striving for preeminence in all fields of flight. Consequently, a subsidized foreign industry puts U.S. manufacturers at a distinct disadvantage. If we wish to compete effectively in world markets, then we must dedicate the talent and resources necessary to advance our technology.

The selection of Jeff Ethell to tell this enlightening story is commendable. Few full-time authors have the skills to communicate technical subjects in other than highly complex terms. Jeff Ethell, an experienced pilot and an accomplished writer, is such a professional.

Besides exploring the intricacies of aerodynamics, energy, and safety, the author reveals a number of little-known facts about some truly incredible achievements in the history of aeronautical experimentation and progress. He not only details what NASA and NACA have done for general aviation over the years, but he also treats us to an impressive look ahead.

Anticipated improvements in tomorrow's aircraft utility, whether the use is for business, agriculture, or some other commercial application, appear just as exciting as the scientific developments in technology.

New concepts in composite materials and metallic structures, along with revolutionary advances in systems integration, will provide the next generation of aircraft with significantly higher performance, reliability, and efficiency. And new innovations in computer technology and production techniques may result in a totally new kind of airplane.

But to achieve these goals will take more than the imagination and ingenuity of design engineers and builders. It will take broad-based public support, a recognition that general aviation is a major contributor to America's economic security.

This is a splendid work, the definitive book on the many technical wonders of a dynamic and vital national asset. That is why I hope it receives the widest exposure possible. In fact, it should be required reading for anyone with even a modicum of influence in shaping our nation's future.

James R. Greenwood
Retired Senior Vice President
Gates Learjet Corporation

PREFACE

General aviation remains the single most misunderstood sector of aeronautics in the United States. Airline companies make the news on a regular basis and travel on the major carriers is taken for granted, yet they comprise but 10% of all U.S. nonmilitary flight operations. The remainder belongs to general aviation, one of the major keys to American business success.

This book will give you a detailed look at how general aviation functions and how NASA helps keep it on the cutting edge of technology in airfoils, airframes, commuter travel, environmental concerns, engines, propellers, air traffic control, agricultural development, electronics, and safety. No doubt some of you will be surprised to find that there is so much activity in general aviation. This is not simply the weekend pilot who wants to take a spin, but also the businessman who relies on aircraft to get him where he is going when he wants to go, the corporation that wants sophisticated jet transportation for its executives, the family that wants to travel where no major airline terminal exists, the farmer who wishes to have his crops protected, the mission pilot who transports spiritual and physical aid over dense jungle terrain, the medivac team that requires rapid transportation for an accident victim or transplant recipient. And the list of benefits goes on.

If there was ever a time when NASA's aid was pivotal to general aviation's survival, it is now. Come along with me, as we take a look into a fascinating and seldom seen world through the eyes of NASA and its numerous programs.

CHAPTER 1

WHAT IS GENERAL AVIATION?

Though few people are aware of it, general aviation, all civil flying activity except airline operations, accounts for 98 percent of the nation's 215 000 aircraft and 96 percent of its 815 000 pilots. It is by far the most active and the most diverse of all aviation operations. When combining the amount of airline and general aviation flying, the airlines account for only 10 percent of the total hours and operations flown. And the majority, around 80 percent by some estimates, of general aviation flying is for business purposes, serving all of the nation's 14 746 airports while the airlines reach only 733 (or 5 percent). The National Aeronautics and Space Administration (NASA) includes air taxi and commuter aircraft under its general aviation research programs while excluding rotorcraft.

Though the public conception of general aviation is that of private owners flying for pleasure, the opposite is true, particularly in these days of less discretionary income. It includes every kind of piloted airborne vehicle from ultralight powered hang gliders and balloons to airline-size corporate jets.

Not only does the business community rely very heavily on general aviation to function, but the U.S. balance of trade is heavily dependent on the export of aircraft. In 1979, civil aircraft sales resulted in a net positive contribution of $10 billion to our trade balance. In the past 20 years, the U.S. share of total exports of the major industrialized nations has dropped by almost one-third, while U.S. civil aircraft export sales have increased ninefold, and now sustain over 60 percent of the total civil aircraft work force.

More than 90 percent of all general aviation aircraft in the world originated in U.S. factories, and the market is growing substantially as foreign commuter airlines are seeking new replacement aircraft. Foreign aircraft manufacturers are producing new turboprop aircraft to meet the need, threatening the U.S. lead in the field.

In the past, NASA's input to general aviation aircraft technology has lagged behind military types and commercial airliners. The majority of today's fleet was built on the aeronautical science that was driving the aircraft industry before and during World War II. With the exception of some new concepts developed by innovative experimental aircraft home builders, and applications of advanced aeronautical technology in a new generation of business aircraft, today's general aviation aircraft would not have looked out of place in the 1950's. As a matter of fact, several designs that originated in the late forties and early fifties are still being produced and have performance equal to many newer designs.

From its inception in 1915, the National Advisory Committee for Aeronautics (NACA) and now NASA have been involved in aeronautical research and therefore have been a part of the progress in general aviation (GA). For example, most designs use NACA airfoils. Recently, more than a dozen contemporary production and prototype GA aircraft have been designed with the aid of new technology gained from NASA programs of the past decade, ranging from twin-jet business aircraft to single-engine trainers. Since the beginnings of NACA, the goal has been to conduct research that industry can use in building better products; but without the talent and engineering in GA companies, there would be no American lead in general aviation. The goal at NASA is to preserve and advance that lead. American leadership in the field, however, is on the wane.

NASA's basic goals for general aviation are continuing improvements in efficiency, safety, environmental compatibility, and utility, broken down into research dealing with aerodynamics, structures, propulsion, and avionics. NASA's Langley Research Center, in Hampton, Virginia, is responsible for the majority of those technology programs in general aviation aeronautics and for flight research. Much of the flying is done out of Wallops Flight Center, Virginia. Wind tunnel testing has been conducted primari-

ly by Langley. In addition, the unique facilities of the Ames Research Center at Moffett Field, California, primarily the 40 x 80-foot wind tunnel, are used for specialized GA research. Propulsion research is done at the Lewis Research Center in Cleveland, Ohio.

These NASA centers have a battery of research facilities which a single aircraft company could never afford, ranging from computers to huge wind tunnels that can test a full-size airplane as if it were in flight. Each one of these research tools can produce results that might not be obtainable in any other feasible or economical way. An initial NASA approach to a problem often is analytical. The next step may be the testing of a small wind tunnel model, or of more elaborate models flown by remote control, either in an adapted wind tunnel or outdoors. Piloted simulators—versatile ground-based machines that duplicate key characteristics of the full-scale aircraft—may be used. Finally, the idea may be tested in free flight on a full-scale airplane flown by NASA's research pilots.

Though NASA has some unique facilities and personnel, GA programs frequently involve industry and universities since NASA cannot do the work alone. Industry has to translate research into practical reality, and if the result will not sell in the marketplace, it has to be scrapped. Since the beginnings of aeronautics, universities have been a primary source of fundamental research capabilities. Without the help and leadership offered in both camps, NASA's research would not be reflected in a final product. As NASA's Dr. Walter B. Olstad said before Congress, "Our reason for existence is solely to provide technological services to our customers."

The continuing growth of general aviation and commuter air service reflects their increasingly important roles in business and in the transportation system. A major reason for this growth has been the restructuring of truck and regional airline routes which has reduced air service to many smaller communities. Since the U.S. has fallen behind in commuter aircraft markets both at home and abroad, many commuter airlines have had to purchase foreign aircraft to meet their needs. Foreign firms, backed financially by their governments, have been able to exploit new market opportunities. Even greater foreign competition lies ahead, spurred by

national determination in several countries to capture greater shares of markets once dominated by the U.S.

A major factor in the future success of the American commuter and general aviation industry is the development of technologically superior next-generation aircraft that are safer, more reliable, more comfortable, and more economical to operate than those of the competition. Unfortunately, industry does not have the technical personnel, facilities, or resources to generate the high levels of technology needed. The availability of this technology in time to influence new aircraft in the next 10 years is, therefore, heavily dependent on NASA's programs.

NASA's current involvement with general aviation is an extension of what has been taking place over the past several decades. In aerodynamics and flight dynamics, emphasis will continue to be placed on safety and energy efficiency. Further, research is needed on stall/spin phenomena of both high- and low-wing aircraft as well as less conventional configurations such as canard (forward) winged aircraft. One promising development has resulted in the segmented, drooped-wing leading edge that can reduce the abruptness and severity of the roll-off at the stall and thereby prevent unrecoverable flat spins. Long-range goals are to evolve design methods that industry needs for safer aircraft, emphasizing simulation and analytical techniques.

Other aerodynamics research is aimed at increased energy efficiency, including work on cooling drag reduction, engine/airframe integration improvements, and further development of natural laminar flow airfoils and aircraft technology. Smooth contours and surfaces, achieved with composite materials, are needed to promote laminar flow. Composites themselves are the subject of a great deal of research due to potential weight reductions of up to 30 percent, reduced drag, and more favorable structural integration.

Propulsion research will concentrate on achieving greater fuel efficiency, reduced weight, lower maintenance, and greater reliability. Work will continue on spark-ignition reciprocating engines, but improvements are required on supercharged two-stroke cycle diesel engines and stratified charge rotary combustion engines. Turbosupercharger research will remain an integral part of the program. Basic research will continue into ignition and

combustion chamber processes, engine cycle modeling, fuel injection, improved cooling, and cooling drag reduction. These advanced engine concepts can lead to improvements in fuel economy of one-third to one-half relative to current engines.

Small turboprop engines are of particular interest for high-performance single-engine or light twin-engine aircraft, but additional research must continue to achieve increased fuel economy and initial cost reductions.

Propeller research needs to emphasize higher aerodynamic performance for greater energy efficiency using advanced blade planforms and airfoils and new concepts for reducing tip losses. Reduced noise and increased performance will be studied while research into use of composites for aeroelastic benefits, lower blade weight, greater structural damage resistance, and improved fatigue life needs to continue. Propeller and nacelle integration studies should be extended to reduce installation and nacelle interference losses.

Ground and flight test of the demonstration advanced avionics system (DAAS) has been one of NASA's efforts to integrate navigation and flight management, thus improving safety and utility. However, these systems must be reliable and affordable to find acceptance, making reliability, maintainability, and low cost major requirements. State-of-the-art electronics have been a major part of this program, which has an integrated data control center used for alphanumeric messages and serves as the primary interface with the pilot. The IDCC can call up various functional checklists, execute specific functions such as autocourse, serve as a data entry point, and even provide a ground data link capability.

Other areas of avionics research include an integrated fluidic flight control system which will hold attitude, altitude, heading, and velocity, and provide glide slope instrument landing tracking. Advanced synthetic voice response digital technology will be investigated as a means of increasing general aviation communication capacities. In addition, methods will be studied for using the azimuth and elevation measured by a microwave landing system (MLS) to fly curved paths without the need of expensive distance-measuring equipment.

Improving means for single-pilot instrument flight rule (IFR) operations is being investigated, including speech recognition and

synthesis techniques to improve air/ground communications, advanced displays, advanced terminal area systems evaluation, and ways of better interpreting and using weather data in flight.

An extensive crashworthiness program is leading toward improved crash safety and occupant survivability, covering three basic areas. One is energy-absorbing structures for seats and fuselage floors to limit the loads imposed on the occupants in a crash. Another is the development of structural analyses to predict large deflection structural response on impact. A third area is controlled crash tests of full-scale aircraft, which has been very successful in studying structural deformation and impact loads. Results of simulating crashes of 60 to 90 miles per hour on full-scale aircraft have led to second-generation load-limiting seats and floors. Computer mathematical models for simulation of occupant/seat/structural analysis have been a basic part of the program as well. In addition, the crashworthiness of the newer composite materials is being investigated.

NASA also has been assisting the Federal Aviation Administration (FAA) in evaluating the crash-activation of emergency locator transmitters (ELT), which general aviation aircraft must carry, in order to recommend improvements.

In agricultural spraying, research has been conducted to improve dispersal and distribution of chemicals or dust applied from aircraft. A primary part of the research involved determining the interactions between the aircraft wake turbulence and the dispersed materials and how a modified aircraft might improve swath control. Wind tunnel and flight tests were conducted and theoretical prediction methods were developed that are now being used by other government agencies, universities, and industry.

The challenges of general aviation will remain the subject of intense research at NASA, within industry, and within the academic community as its utility increases. The Commuter and General Aviation Research and Technology Program of NASA's Office of Aeronautics and Space Technology provides a glimpse into the future of aviation's most active arena.

CHAPTER 2

AERODYNAMIC EFFICIENCY

At the heart of NASA's general aviation research efforts lies the desire to improve aircraft efficiency: in other words, to explore areas that will allow aircraft to fly farther and faster on less fuel with improved passenger comfort and safety. Basic to this goal is research dealing with high lift/drag airfoils, supercritical aerodynamics, natural laminar flow, composite structures, and drag reduction.

Laminar Flow

As fuel prices climbed in the early 1970's, fuel efficiency took on ever-increasing importance and research efforts were intensified to reduce aerodynamic drag. As a result, NASA has made significant progress in reducing parasite (zero-lift) drag and induced (caused by lift) drag. The drag reduction challenge is to reduce skin friction, which accounts for about 30 to 50 percent of an aircraft's drag at cruise. NASA's approach in reducing drag has been multifaceted, including use of both laminar and turbulent boundary layer control. Keeping the boundary layer (the air layer closest to the skin) on a surface laminar, or thin and smooth, can reduce skin friction by as much as 90 percent. Very smooth and controlled pressure gradients can delay the boundary layer transition to turbulent flow and produce significant regions of natural laminar flow (NLF).

For years, designers of general aviation aircraft, particularly of light single- and twin-engine types, have used the "four-digit"

The Cessna Citation III uses the NASA supercritical airfoil to obtain a high-aspect-ratio wing. The company found it could use relatively thick wing sections and still achieve efficient Mach 0.8 flight. The thick section minimizes the weight of the high-aspect-ratio wing (ratio of wing span to width or chord), and provides a large volume for fuel storage. (Cessna Aircraft)

series of airfoils developed by NACA as far back as the 1930's. As a matter of fact, very few aircraft flying today, including Cessnas from the Airmaster to today's Skyhawk and Skylane, incorporate airfoil technology radically different from that used so successfully prior to and during World War II. One of the major developments of the late 1930's was the six-series of laminar flow airfoils which, though not totally successful in producing laminar flow using the existing construction methods, went a long way toward improving the aerodynamic art.

Wings, stabilizers, propellers, and control surfaces use airfoils that can be improved to promote laminar flow (less drag). A modern, properly constructed laminar flow airfoil is generally considered one that can achieve laminar flow over the first 70 percent of the upper and lower surfaces over a reasonable range of angle of attack and speed/altitude.

With laminar flow the air particles move in smooth, parallel (laminated) layers over the surface, each with a constant velocity and motion relative to its neighboring layers. Turbulent flow

results when these laminated layers break up, resulting in higher friction drag. The problem of maintaining extensive laminar flow is made more difficult by rivets, dents, bumps, joint overlaps, manufacturing imperfections, and even bugs that have hit the airfoil. However, the problems inherent in achieving laminar flow are considered worth solving to obtain improved cruise speeds which mean less fuel burned for a fixed distance.

After the four-digit series NACA developed the five-digit airfoils in order to provide airfoils with better maximum lift. They were applied to such well-known products as the Beech Bonanza, Baron, and King Air. But these four- and five-digit airfoils, while providing increased improvements in lift, promoted turbulent flow because of their shape.

NACA researchers knew this to be the case even in the 1930's so laminar flow was singled out for more intensive investigation. The six-series airfoils, when achieving laminar flow, can reduce drag up to 50 percent over the older series but the airfoil surface must be very smooth (minimum waviness). In addition, due to the sharp nose radius the six series does not have very high maximum lift capability. The use of bonding and composite materials (smooth surfaces) in the last few years has opened the doors to achieve extensive natural laminar flow.

In the 1950's, NACA left low-speed airfoil research to concentrate on transonic and supersonic designs. Out of this research the so-called supercritical airfoil, optimized for drag reduction at high subsonic cruise, had camber located near the trailing edge with improved lift over drag (L/D) at higher cruise lift coefficients. In the early 1970's, a low-speed derivative of supercritical airfoil technology was developed for use on general aviation aircraft. Though the resulting GA(W)-1 was not a true supercritical airfoil, it paved the way for general aviation manufacturers to obtain improved L/D benefits. At that time, the GA industry was not optimistic in achieving laminar flow because of the old problems of rough surfaces, but it did want a better turbulent flow airfoil. In this regard, NASA developed an airfoil with higher maximum lift—the GA(W)-1, now known as the LS(1)-0417—and improved L/D at climb-out speeds. This was particularly beneficial for improved performance (safety) on twin-engine aircraft with one engine out.

Both the Beech Skipper and the Piper Tomahawk light trainers were designed and built in the mid-1970's using the new airfoil. The result for both of these aircraft was a very low stall speed, ideal for traffic pattern training. The tradeoff came with decreased efficiency at normal cruise speeds, but that was not to be the primary purpose of either aircraft since they would be used primarily for training near airports. Due to the aft camber of the wing and the resulting high pitching moment, flap deflection was limited to provide drag for approach angle control rather than to decrease stall speed.

NASA improved the GA(W)-1 by moving the camber forward, thus increasing lift and decreasing the pitching moment at the cost of less docile stall characteristics. The GA(W)-2 or LS(1)-0413 was a subsequent development.

With improved construction techniques that could eliminate most of the surface roughness problems which restricted laminar flow, NASA developed a new series of airfoils in the mid-1970's that would combine the high maximum lift of the LS series with the low drag of the six series. With the NLF(1)-0416 and NLF(1)-0215F, natural laminar flow became a realistic possibility. Even if extensive laminar flow does not occur, high lift still exists and the drag will be no higher than on a turbulent flow airfoil of the same thickness.

The NLF(1)-0215F, flight tested in glove form on a T-34C, uses a flap that can be deflected upward 10 degrees at cruise, much like high-performance jet aircraft, to achieve the best L/D for both the low- and high-speed regimes. This will be particularly beneficial for the new generation of GA high-performance, single-engine aircraft designed to cruise at 300 miles per hour at 25 000 feet. An advanced NLF supercritical airfoil was also flight tested on a modified F-111 over a range of wing leading-edge sweep angles from 10 to 26 degrees at Mach numbers from 0.8 to 0.85. The experiment also showed that significant laminar flow could be achieved at off-design cruise conditions of Mach number and leading-edge sweep. This is particularly important for commuter and business jet transport aircraft (see chapter 5).

Cessna believes that its pressurized 210 is a prime candidate for benefiting from a wing that can achieve natural laminar flow. Collaborating with NASA, Cessna has conducted a laminar flow

visualization program on a 210 wing using chemical spray in the Wichita State University wind tunnel to verify NLF potential. With a 375-horsepower turbocharged engine, the 210 can reach over 30 000 feet where high true airspeeds are obtained.

NASA conducted a study of the benefits of cruise design optimization for high-performance, single-engine airplanes with a cruise speed of 300 knots and a cruise range of 1300 nautical miles with six passengers. The results revealed that these performance estimates could be reached with fuel efficiencies competitive with present-day, slower flying aircraft. But the major achievement would be the potential for 200 to 400 percent greater fuel efficiency than is achieved by current twin-engine airplanes capable of similar cruise speeds, payloads, and ranges.

NASA conducted flight tests to see just how much laminar flow was being achieved on eight different airplanes with smooth, thick-skinned, bonded, milled aluminum, or composite wing surfaces. Tests were conducted on smooth portions of the Cessna P210 and Beech 24R. Extensive tests also were conducted on the Bellanca Skyrocket II, Lear 28/29, and three Rutan Aircraft Factory designs, the Long-EZ, VariEze, and Biplane Racer, which utilize modern construction materials and techniques to provide aerodynamic surfaces without significant roughness and waviness. Previous flight experiments involving laminar flow measurements were limited to either airfoil gloves or specially prepared (filled and sanded) wing sections. Only sailplanes were achieving significant laminar flow without modification. For the later tests, no preparation of the aircraft was allowed; they were "production quality" straight out of the factory.

The results were more than encouraging. There were extensive areas of NLF on all the aircraft tested, making laminar flow a very practical possibility on modern production aircraft. Even with propeller slipstream effects it was found that the laminar boundary layers were not destroyed completely, changing previous conclusions. Thus, NLF airfoils may provide drag reduction benefits, even on multiengine configurations with wing-mounted tractor engines. On swept wings, particularly in the high-speed cruise regime, spanwise flow contamination at cruise was found not to be as much a concern for laminar flow. Laminar flow on winglets appears very promising as well.

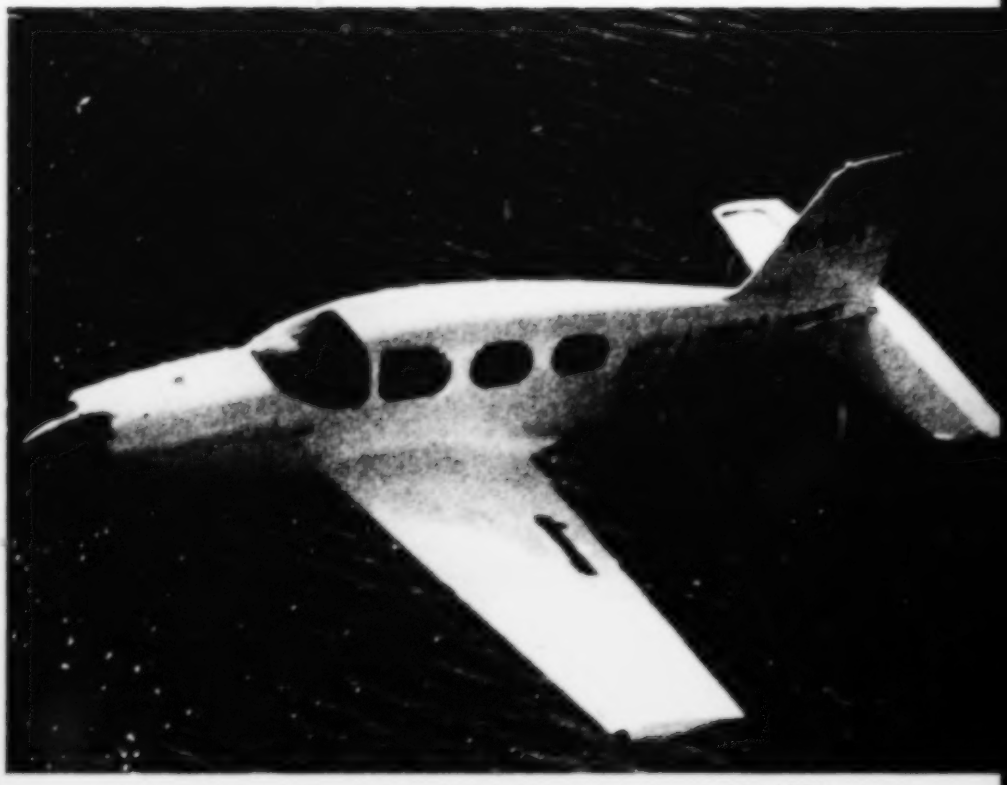
Insect impact contamination has always been a problem in achieving laminar flow, but the insect debris pattern collected on a NACA six series airfoil revealed only one-fourth of the strikes to be of sufficient height and in a position to cause transition. A combination of the newer NLF airfoil geometries and mission profiles could minimize the sensitivity even more. Natural laminar flow is no longer out of reach for nonspecialized aircraft; it can be achieved not only on current production aircraft (up to 70 percent in some cases) but to an even greater extent on future designs without great expense.

Computers and Airfoil Design

The use of computers is one of the important factors in the design of airfoils to reach the projected efficiencies. NACA used to produce catalogs of airfoils that designers would ponder over, test, retest, and finally apply to an airframe. It could take up to one week using a mechanical calculator to come up with a single pressure distribution; the same calculation on a modern computer takes one second. A designer can load in cruise speed, stall speed, weight, lift coefficient at various speeds, and other aerodynamic data, then custom design a unique airfoil from NASA-developed codes. The structure can be optimized rapidly, with less emphasis on percentage thickness of the wing, and the airfoil will more closely suit the purpose. New GA aircraft such as the Mooney M301 have derivative airfoils developed from NASA codes. Performance verification of the completed designs can then be tested in model form in NASA wind tunnels or can be tested full scale in the 30 × 60-foot tunnel at Langley or the 40 × 80-foot tunnel at Ames.

NASA has developed a low-speed airfoil design program for a minicomputer. Though the program is limited to some degree, it is certainly a start in placing airfoil design at the fingertips of most people around the world who have access to a minicomputer that will program in BASIC on an 8K core.

An airfoil design institute has been established by NASA at Ohio State University using a NASA-maintained data base. Any customer can obtain an optimized airfoil section, drastically reducing the time needed to advance the state of the art. This can



The black painted wing on this Bellanca Skyrocket II allowed NASA/OSU researchers to visualize chemicals applied to measure natural laminar flow (NLF). The aircraft, constructed of fiberglass composites, proved to be extremely smooth aerodynamically, with laminar flow extending from the wing leading edge for approximately the first 50 percent of the wing's surface. This greatly advanced NASA NLF research.

have a significant effect on reducing costs in the general aviation industry.

Without a stable NASA research base, many U.S. companies would find themselves unable to produce aircraft competitive with the world market. A good example is the Learjet business jet, which was designed and developed from a Swiss fighter in the early 1960's by a group of less than 100 engineers with little wind tunnel testing, limited computer facilities, and little specialized

Using the NASA/Ohio State University airfoil program, Mooney Aircraft incorporated a natural lami ar flow wing on its new pressurized 301. Cruise speeds of 260 mph (top speed 301 mph) at 25 000 feet will give a 1150 statute mile range at 14.5 miles per gallon. NASA's participation in computer and wind tunnel testing contributed to this breakthrough for a six-seat general aviation aircraft. (Mooney Aircraft)

equipment necessary to develop a high-performance aircraft. Instead, Bill Lear and his associates relied heavily on the basic technology that NACA and NASA had developed over decades of research. Learjet wings and tails employed modification of NACA airfoil sections developed in the late 1930's and early 1940's. One of the first Learjets built was mounted in NASA Ames' 40 x 80-foot wind tunnel for testing in 1966, yielding a great deal of data on this first business jet. The wing flap design was developed directly from the experimental work of NACA.

Winglets

Though several Rutan designs have employed NASA-developed winglets to excellent advantage, the Gates Learjet Model 28 became the first production aircraft to fly with them. Now the Model 29 and 55 Longhorn are flying with the winglets. Cruise fuel

Among the engineering challenges incorporated in the Gulfstream III were NASA winglets and airfoil, along with composite primary structures. Drag improvement was significant, resulting in better fuel consumption and higher performance. (Gulfstream Aerospace)

flows on the Model 28/29 are around 26 percent lower for the same payload/speed combination. Takeoff and landing performance also has been significantly improved. These improvements resulted from several factors: the aircraft can operate at higher altitudes due to the wing extensions (6 feet plus winglets each side) where fuel consumption is reduced, and drag has been reduced by removing the tip tanks, increasing the aspect ratio, and adding the NASA-developed winglets incorporated on the Gulfstream III as well with great success.

The winglet itself reduces vortex drag by producing a forward lift component somewhat similar to sails on a boat. At high lift coefficients this effect more than offsets the drag due to the winglet itself. Winglets also significantly increase the lifting surface or aspect ratio of the wing, though a penalty of additional structural weight must be considered. While there is great potential for winglets on many different designs, each winglet must be tailored for each design in order to achieve the desired results.

Gulfstream Aerospace carried use of NASA research over into their Commander Fanjet 1500 with the possibility of natural laminar flow wings and winglets. Winglets improve wing span efficiency by positive control of the tip vortex flow field, reducing drag due to lift. The cockpit of the 1500 also will incorporate much of the NASA single pilot IFR research. (Gulfstream Aerospace)

Composite Materials

Since 1970, NASA has actively sponsored flight service programs with advanced composite materials—essentially woven cloth impregnated with fibers of carbon or other high-tensile strength materials—particularly on commercial transports and helicopters. Composite aircraft structures have the potential to reduce airframe structural weight by 20 to 30 percent, reduce fuel consumption by 10 to 15 percent, and thus reduce direct operating costs (DOC). NASA, primarily through its Aircraft Energy Efficiency (ACEE) program, has tested all types of composites from advanced fiberglass to graphite epoxy in real-world flight regimes, accumulating over 2.5 million total flight hours.

The applications to general aviation can be significant, as shown by Rutan Aircraft Factory and another Rutan company, Scaled Composites. They have built and flown several aircraft that are

basically total composite structures and that have been proven both safe and very fuel efficient. Not only are composites extremely smooth, lending themselves to laminar flow, but they can be made stronger and lighter than most aluminum designs. Crashworthiness remains a NASA concern since composites have been labeled as too brittle and unable to absorb enough energy during a crash. However, new construction techniques have helped composites absorb the impact of a crash. NASA hopes to "crash" composites in controlled tests, possibly with an all-composite helicopter prototype.

One of the major problems in using composites centers around reducing production costs. Small GA companies (at least in relation to the larger military and transport manufacturers) would have to find major sales opportunities in order to recoup retooling costs. In the far term, the ideal is that composite manufacture can be automated far more than with metal construction techniques.

The Lear Fan made a radical departure from past general aviation aircraft since it was built almost entirely of composites, promoting light weight and low drag. It used slightly more than 200 gallons of fuel to travel 2000 miles, while cruising at 400 mph. (Lear Fan)

In the near term, manufacturers are looking for ways to eliminate large autoclaves required to set up the materials and go to thermal stamping and forming. In other words, composites could be simply heated and stamped out. Inherent in any transition to composite manufacture is retraining of workers, a major expense regardless of how efficient construction methods are.

The most aggressive use of composites and new NLF airfoils can be seen in Bill Lear's last design before his death, the Lear Avia Learfan 2100, built almost entirely of graphite composites. The only metal components other than the engine are the landing gear, propeller hub, and many small structural fittings. Even the propeller blades are made of Kevlar-epoxy. With a custom computer-designed airfoil and all-composite construction, it has a maximum cruise speed of around 360 knots. Unfortunately, the company folded after being unable to obtain FAA certification.

Two other all-composite aircraft that do appear to be heading for production are the Beech Starship and the AVTEK 400. Both are twin-turboprop designs with canard surfaces and high cruise speeds. Fuel economy and efficient payloads are major benefits of these aircraft which are radical departures from the GA norm, very possibly the shape of the future.

Gates Learjet (not related to Learfan) is looking into its next-generation product as suitable for secondary composite structures. Current Learjets utilize fairings that are composite or composite based with new fiberglass/Nomex core materials. Learjet is also looking at primary composite use on forward swept wings, but the cost of building the wings is still too high for the few units that would be produced. The company is looking for ways to bring the price down since composites are the only avenue to creating a wing stiff enough to resist the strong torsional/bending moments inherent in forward swept wing designs.

Cessna Aircraft Company incorporated a substantial amount of NASA research in its new Citation III business jet, which features a swept, supercritical wing and bonded-riveted airframe construction with selected use of composites. The wing is not only designed to push cruise speeds up due to delaying the drag rise shock wave effect, but the smooth bonded surface promotes some laminar flow. Kevlar, graphite, Nomex core, and fiberglass composites are being used for flap sections, spoilers, engine nacelles,

Gates Learjet is among the companies that depend on NASA for advanced research. Gates builds several versions of the Learjet, including the Model 55 Longhorn, so named because it uses NASA winglets. (Gates Learjet)

seat structures, and some fairings and doors. Both the Canadair Challenger and the Mitsubishi Diamond I have supercritical, high-aspect-ratio wings as well, reflecting NASA's pervasive influence on aerodynamics regardless of country of origin.

CHAPTER 3

INTERNAL COMBUSTION ENGINES

From the early days of aviation the argument between aerodynamicists and engine specialists over what drives aircraft design has never been satisfactorily resolved. Does aerodynamic function determine needed power or does available power determine aerodynamic form? Though the debate will most likely never be resolved, engine development has usually opened the door for advances in aerodynamics, for without power aircraft cannot fly. Needless to say, there are exceptions to this rule, particularly in soaring and aircraft that become gliders like the Space Shuttle.

Overall, there have been no major design changes in general aviation aircraft engines since World War II. The air-cooled, internal combustion engine fueled by high-octane gasoline continues to power many of the new designs rolling off the industry's production line. Major changes are needed to increase fuel efficiency and utility, from the smallest trainers to the largest multiengine corporate transports and commuter airliners.

While general aviation manufacturers have been seeking improved safety and improved air traffic control, the heart of their survival as companies lies with energy efficiency. If aviation gas (avgas) becomes unavailable or unreasonably expensive, then these aircraft will have to be adapted to use autogas, diesel, or jet fuel. Based on relative Btu content and production costs per gallon, the kerosene/diesel-type fuels also offer an inherent economic advantage of 20 percent or more over gasoline. With 1985 avgas prices over $2.00 a gallon in the U.S., over $5.00 a

gallon in Europe, and just plain unavailable in many parts of Africa and the Middle East, the writing is on the wall.

Environmental Concerns

The heart of NASA's general aviation propulsion research can be traced to an initial concern with meeting standards set by the Environmental Protection Agency (EPA) in the early 1970's. An exhaust emissions reduction program was initiated in 1973 between the Federal Aviation Administration and NASA. A year later Teledyne Continental Motors and Avco Lycoming were under contract for emission-reduction testing through a number of avenues. The 1974 fuel crunch then changed priorities to fuel economy, sending industry and NASA off a springboard that led to the advanced engines discussed in chapter 4.

Even though most of NASA's current engine research is devoted to improving efficiency, noise and exhaust emissions in general aviation power plants remain a concern, particularly since they are perceived by the public as major annoyances. There are about 14 100 suburban airports in the U.S., most of which are located in small communities with no buffer zones and with people living nearby. Therefore, general aviation has the potential for greater community reaction to noise and pollution than commercial and large transport aircraft. In addition to the community noise, passengers and crew experience a great deal of noise and vibration, particularly in the smaller aircraft.

The exhaust emissions reduction program continued with both Teledyne Continental and Avco Lycoming. These engine manufacturers successfully pursued program goals even though the EPA lowered its emission standards in 1979.

Teledyne Continental Motors investigated and developed three aircraft piston engine concepts to reduce emission of hydrocarbons and carbon monoxide while simultaneously improving fuel economy by improved fuel injection, improved cooling cylinder head, and exhaust air injection. Variable ignition timing also was explored. After investigating each system and incorporating them into a IO-520 engine, the company conducted test flights with a new Cessna 210 Centurion single-engine aircraft.

The 210 handled and flew well with the prototype engine; the

only adverse result was backfiring in the exhaust after rapid throttle closing, a problem easily solved by shutting off air injection at lower than normal manifold pressures. For a 328.8-statute-mile flight, the prototype engine with standard fixed magneto timing got 6.3 percent better fuel economy over the baseline engine, primarily in climb, enroute climb, and approach modes.

The tests revealed that the EPA standards for carbon monoxide, hydrocarbons, and nitrogen oxide could be met using exhaust air injection alone with no improvement in fuel economy or by using only the Simmonds improved fuel injection system to provide a leaned fuel schedule. The use of exhaust air injection in combination with exhaust port liners reduced exhaust valve stem temperatures to levels below that of the baseline engine, which could result in longer valve guide life. Use of exhaust port liners alone can reduce cooling air requirements by at least 11 percent or a 1.5 percent increase in propulsive power. A fixed ignition timing of 27 degrees BTC (5 degrees over standard) provided a test bed fuel economy improvement of 2 percent in cruise but this could not be substantiated in flight testing.

The basic purpose of the contract was met by improving fuel metering for better fuel-air ratio control, reducing heat transfer from exhaust gases to cylinder heads, and oxidation of exhaust pollutants, even though the hardware used may not represent the most cost-effective means of obtaining these results. The fuel injection system could prove too expensive for production, and thermal barrier coatings or improved exhaust port design might produce benefits similar to those obtained with port liners at less cost. A similar argument could be made for oxidation of exhaust pollutants by air injection.

Avco Lycoming approached the contract investigating high-energy multiple spark discharge and spark plug tip penetration, ultrasonic fuel vaporization, and variable valve timing. Since the company did not include flight testing as part of the program, it used three different engines for the bench tests, the TIGO-541, 0-320, and IO-360, respectively.

Several ignition system configurations were evaluated: capacitive discharge, multiple spark and staggered spark, and various other spark plug configurations. Test results revealed that none of these resulted in a consistent, significant improvement

over the standard ignition system. Neither the spark duration nor spark plug tip locations were considered to be limiting factors for improving performance or emissions.

Ultrasonic fuel atomization gave a significant improvement in cylinder to cylinder mixture distribution at one engine condition but there was no improvement in total engine emissions, fuel economy, or performance. As a matter of fact, a 3 to 5 percent loss in rated full throttle engine performance resulted from the additional manifold restriction of the ultrasonic unit.

Optimum valve timing sequences for each specific engine condition, rather than only at rated power output, revealed little improvement over the standard high-speed valve timing already employed in the company's engines even though improvements in engine performance up to 13 percent at certain off-rated conditions were obtained. Over the ranges tested and at constant fuel air ratio, valve timing did not influence carbon monoxide emission levels. Additional testing, conducted to evaluate the effect of induction system tuning on these results, showed that performance improvements of the same magnitude could be accomplished with standard valve timing and a revised induction system. Considering the magnitudes of the overall performance improvements and due to the greatly increased complexity of the variable valve timing system, induction system tuning was determined a more viable concept for improving overall engine performance.

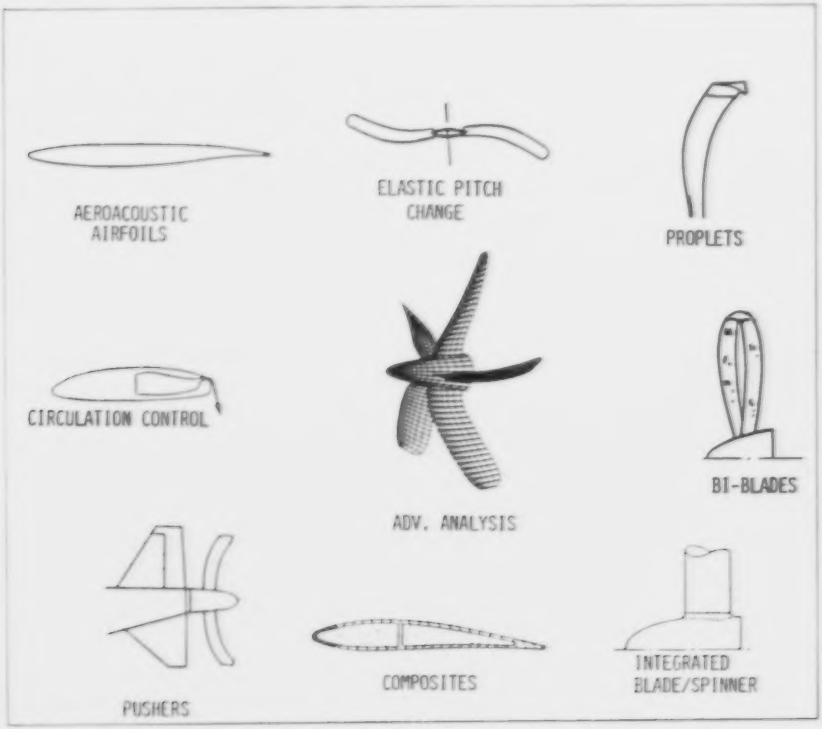
Noise

NASA's general aviation noise research has been conducted through three primary areas: noise prediction technology, propeller noise/performance optimization, and interior noise reduction. The majority of the work has centered around propellers. Turbine-powered aircraft with newer, quieter fan engines do not produce as much noise as turboprops and piston-engine GA aircraft.

Prop-driven light aircraft have been a source of NASA research for many years. One of the earliest programs to develop a quiet aircraft led to a five-bladed prop test bed with extensive muffling; the aircraft was extremely quiet but was far too heavy to be efficient. In 1975 the NASA Acoustics Division was organized and interior noise was targeted for extensive research.

Propeller noise prediction, comparing measured and calculated noise, was quantified using a Twin Otter. Sound pressure level was understood as a function of frequency expressed in multiples of the blade passage frequency. A microphone mounted on a boom on the aircraft's wing was used to take acoustic data. Wind tunnel tests were also conducted.

A Rockwell 500B was experimented on to obtain data but it was never flown. With source noise left to other departments, the acoustics team worked on sidewall design and treatment as their primary area of research. Working with Rockwell, noise was measured outside and inside the standard aircraft. Various treatments were made to lower the noise level, but it was still unclear as to what improved noise levels. The present push is to discover why noise does what it does rather than how.



Advanced general aviation propeller concepts

A Cessna 172 was used to study structure-borne interior noise transmission. The findings resulted in a 10-decibel interior noise reduction through engine vibration isolators. Interior noise, however, has remained a minor issue since it is a customer issue, whereas external noise is an issue for the community at large. GA manufacturers have not studied noise per se due to a lack of sales impact. Now NASA is doing the research, thus saving the high economic risk involved.

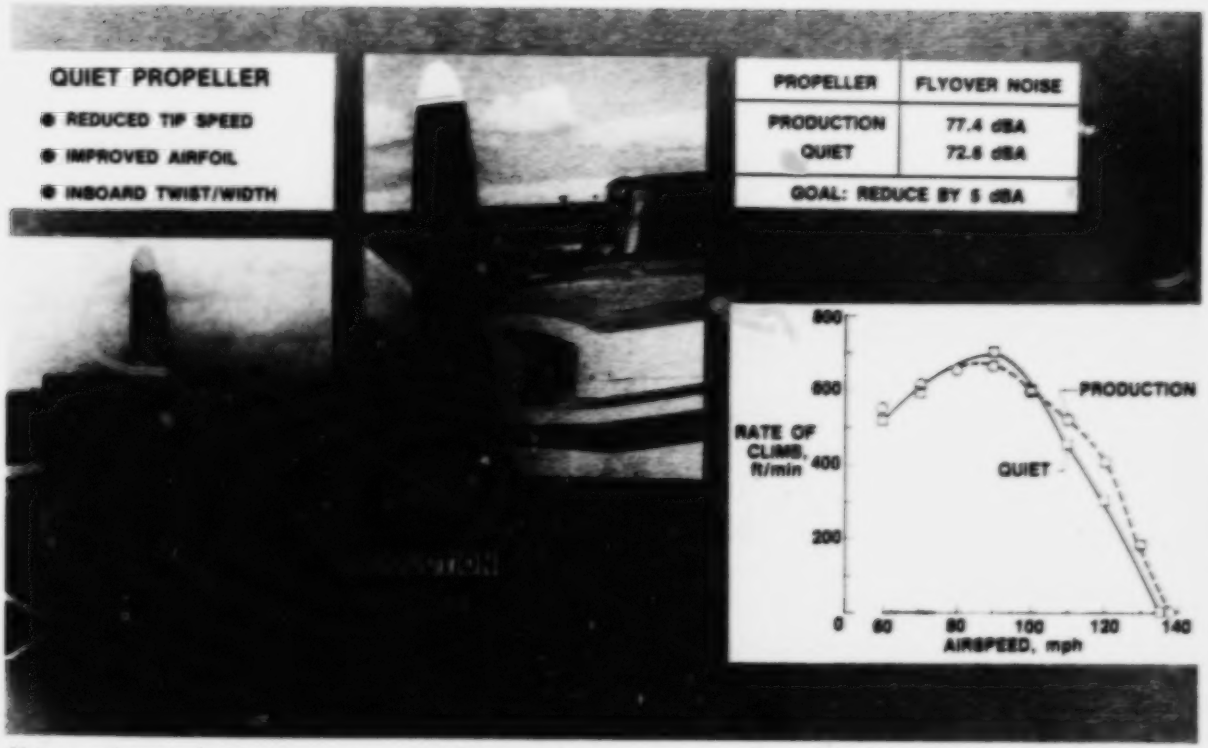
NASA has continued to focus design methodologies on quiet, efficient GA propellers. NASA, EPA, and the Massachusetts Institute of Technology used a Cessna 172 to demonstrate a 5-decibel flyover noise reduction without loss of performance. Computer codes were then created, with the most promising singled out for flight testing.

Ohio State University (OSU) took on the aeroacoustics propeller flight test program with a Beech Sundowner, testing five different propellers of small diameter (three two-bladed, one three-bladed, and one four-bladed). The ideal was to keep performance while lowering noise. A 4.8-decibel decrease in noise was achieved with negligible performance losses. Both the three- and four-bladed props were successful while questions remain on the two-bladed versions.

Another flight test series directed by OSU was run at Lewis on an Aero Commander with three different props at 700 horsepower. The props, built by Hartzell, Dowty Rotol, and Hank Borst, were tested in the tunnel, then on one engine on the aircraft while measuring noise. While there was little difference in noise levels, the performance curve showed each prop to be different in cruise. Noise in the climb configuration, the worst case on the curve, has been singled out as the primary area of testing.

The major effort in these programs has been reduction of prop diameter to lower tip speed, while shifting the aerodynamic load inboard with thinner, wider chord blades. Whether the noise reduction designs will be used by industry to produce new propellers will depend of whether noise reduction affects the owner/operator's performance.

Interior noise reduction involves altering the characteristics of the sound path from the source to the observer, as well as altering the characteristics of the noise source itself. Vibration remains a



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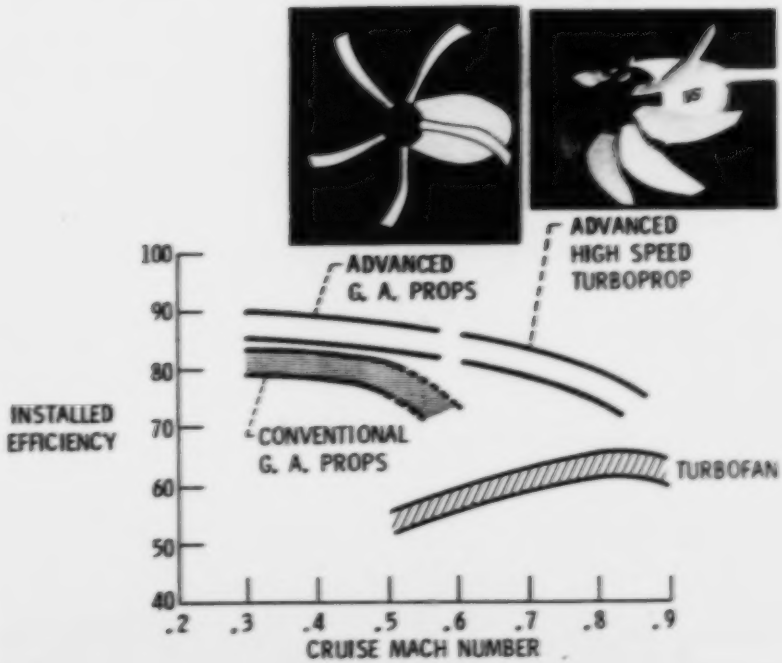
Noise continues to be a major concern of NASA general aviation research. Small single-engine aircraft propeller noise has been investigated under NASA contracts at both MIT and OSU with major success.



Advanced general aviation and high-speed turboprop propellers offer cruise efficiency trends that could increase fuel economies.

major source of interior noise in light aircraft, originating in the engine and transmitted through the support structure into the cabin.

Research efforts have been centered around prediction of structurally transmitted noise and development of noise control methods involving control of both noise radiated from panels to the aircraft interior as well as noise transmitted through the engine mounting vibration isolators. Fuselage sidewall transmission is very important for those aircraft with wing-mounted propellers operating close to the fuselage sidewall. An Aero Commander 680 was modified with 15 pounds of asphalt type, glue on mass. The results indicated that even a modest amount of added mass may

reduce interior noise by 4 to 15 decibels depending on the frequency of the noise.

NASA's overall priorities have reflected the industry's needs by addressing energy efficiency directly, both by improving fuel consumption and looking into burning less costly, readily available future fuels. Lewis Research Center scientists and engineers have centered their research on improvements to existing engines, advanced intermittent internal combustion engines, rotary power plants based on the Wankel engine, stratified charge power plants, cooling drag improvements, and advanced propellers. The new generation of more efficient turbine and turboprop engines is covered in chapter 4.

Ideally, the advanced intermittent internal combustion engines should be able to use any of a number of fuels, primarily jet fuel since aviation gasoline continues to be a very small portion of the fuel produced by the major oil companies. These engines should burn less fuel more cleanly in a power plant of lower weight.

The rotary and two-stroke, stratified charge engines are being tested by NASA in prototype form, showing significant performance advances when compared with conventional production internal combustion aircraft engines.

Air-cooled power plants dissipate much of their heat by radiation from multiple fins formed as part of the cylinders. Researchers found cooling improvements could be made by designing the fins to optimize size and spacing, coupled with cowlings redesigned for optimum aerodynamic efficiency. The end result has been less drag and maximum cooling.

Improving the Piston Engine

While turbine engine development has been actively pursued since the 1940's, piston engine research as a whole has been frozen since World War II with no major advances over the air-cooled reciprocating engine. With work progressing on the GATE (general aviation turbine engine) program, NASA decided to open the doors for the first time in 40 years on near-term improvement of conventional air-cooled spark-ignition piston engines and on future alternative engine systems based on all new spark-ignition

piston engines, lightweight diesels, and rotary combustion engines.

NASA's conventional piston engine research involves applying existing technology to improve fuel economy by 20 percent through leaner operation, drag reduction, and flight at high altitudes where fuel economy is improved. Reduction of exhaust emissions, improved cooling and installation drag, improved fuel injection systems, and advanced turbochargers are part of these efforts as well.

Under a NASA contract Teledyne Continental Motors began research and development of methods to improve fuel economy and reduce the exhaust emissions of its aircraft piston engines. Four concepts emerged permitting leaner operation and reduced emissions of hydrocarbons and carbon monoxide: (1) a timed, air-density-compensated fuel injection system to replace the familiar low-pressure continuous-flow system; (2) a thermal barrier exhaust port liner for improved cylinder head cooling; (3) air injection, when combined with the exhaust port liners, that reduces exhaust valve stem temperatures below those of the baseline engine while increasing oxidation in the exhaust; and (4) variable spark timing to maintain best power spark timing over a broader engine revolution-per-minute operating range.

Compared with the standard IO-520 engine, the version with these four concepts met EPA standards along with a 10 percent improvement in high-performance cruise fuel economy. After being tested, the TSIO-520BE version now being installed in the Piper Malibu utilized many of these improvements along with dual AiResearch turbochargers run from separate exhaust manifolds. A common exhaust manifold would have been subject to pressure waves from one bank pulsing into the other, causing detonation. Divorcing the exhaust for the turbochargers has allowed leaner mixtures without exceeding allowable peak exhaust temperatures. Aftercoolers also helped since induction temperatures were lowered from 300° F to 115° F, further reducing the detonation problem. Not only were exhaust emissions down, but the turbos and slower prop revolutions per minute are natural noise reducers.

In 1979 a joint effort was launched at Lewis and Ames to develop and demonstrate performance and economy improvement of piston engine aircraft via reduced cooling and installation

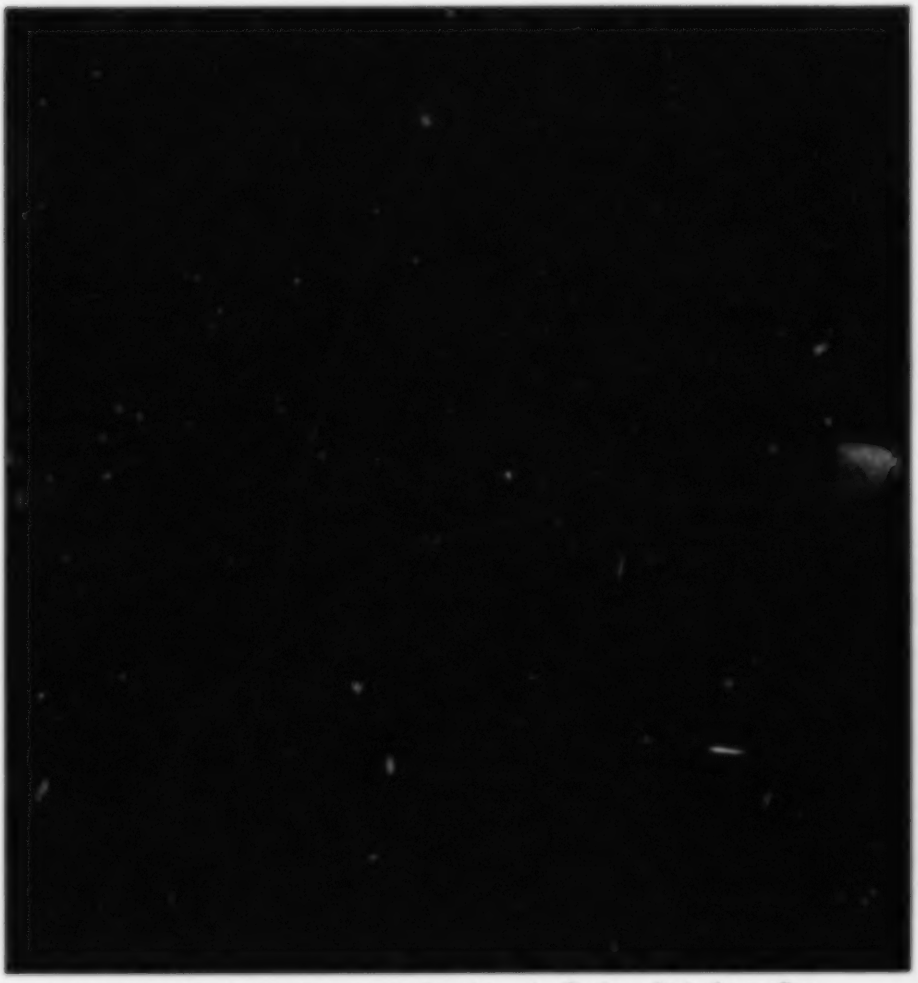
drag. Contemporary engine cooling and installation designs are based in part on technology and data developed for radial engines in World War II. This data base is not adequate for precise design of an engine installation using the common GA horizontally opposed engine.

Estimates were made showing that cooling drag for current designs ranges from 5 to 27 percent of the total airplane cruise drag. A semispan wing/nacelle section from a Piper Seneca light twin was mounted in the Ames 40 x 80-foot wind tunnel for full-scale tests. A cooling drag penalty of 13 percent of total airplane cruise drag was found, defining a baseline for horizontally opposed designs for the first time.

It was clear that an integrated approach to engine cooling, including reduced cylinder cooling requirements and improved internal and external aerodynamics, could reduce this drag penalty by at least 50 percent. Next, a propeller driven by an electric motor and various cooling inlet openings were tested. The propeller slipstream reduced flow separation over the aft part of the nacelle and at the inlets, leading to a marked reduction in total drag. When the inlet area was reduced, drag increased due to inlet spillage, particularly in the high angle-of-attack climb configuration. Inlet pressure recovery in cruise improved as much as 5 percent because of the slipstream effect. For climb, the improvement was around 20 percent for the production (large) inlet and even more for the smaller inlets. These improvements were partially a result of pressure rise related to propeller slipstream, but the major effect was the reduction in the amount of flow separation inside the recontoured inlet at higher angles of attack.

Next, an actual engine was installed in the nacelle with three cooling air inlet sizes. Tests were run over a freestream velocity range from 50 to 150 knots, an angle-of-attack range from 0 to 10 degrees and a cowl-flap deflection range from 0 to 30 degrees.

Tests were also run using exits for the cooling air, located on the sides of the nacelle instead of the usual cowl flap exit under the nacelle. The exit most forward of the wing resulted in least drag but with a lower flow rate than that with the cowl flap 30-degree configuration. If cowl flaps could be eliminated, cooling drag could be reduced 7 percent, and it was found through surface pressure measurements on the nacelle exterior that the pressure



An electric motor-driven propeller was used to determine final results in the cooling drag tests. Important changes have been recommended in nacelle shapes and sizes.

in the lower plenum could be reduced more by using the pressure field of the wing than by deflecting the cowl flap to 30 degrees.

Further, inlet designs providing higher pressure recovery and use of improved cooling exits integrated into a lower drag nacelle proved beneficial. By adding a diffuser to the inlet, pressure recoveries of up to 95 percent were demonstrated. That improvement alone could eliminate most of the need for a cowl flap and thereby save up to 3 percent of total aircraft drag. The high drag is

mainly a result of the current blunt shape and sharp corners of the front of the nacelle, which cause an increase in boundary layer thickness, resulting in flow separation around the inlet and behind the nacelle.

Though this first cooling drag program is now over, the door has only just opened since a computer simulation code is needed to find optimum external nacelle shapes and inlet geometry. Then NASA can begin to conduct computer simulations of new designs and to what extent they can reduce that typical 13 percent cooling drag on GA aircraft.

Studying the combustion process itself has been of major interest to both NASA and industry. Combustion-diagnostic instrumentation has been designed at Lewis to determine on a per cycle, per cylinder basis, real-time measurements of the indicated mean effective pressure and percent mass of charge burned as a function of crank angle. These systems are being used by both the aircraft and automotive industries. Ionization probes, placed in the cylinder head to measure flame position and thickness as a function of crank angle, have proven valuable. Laser Doppler velocimetry (LDV) measurements of the velocities and turbulence levels for cold flow within the combustion chamber have been developed through a grant to Carnegie-Mellon University. A unique charge sampling system at Lewis measures the local fuel-air ratio within the combustion chamber at selected times in the cycle of an operating engine.

This type of instrumentation has been extremely valuable in studying the role of turbulence and gas motions in combustion chambers. A principal goal is to formulate a general mass of charge burned equation that includes engine air-fuel ratio, speed, and torque. Out of this has come development of a theory and multidimensional computer code for future engine design and improvement.

Research also is being conducted to improve the inlet-port fuel injection system by extending the lean limit, requiring a more complete understanding of the relationship of the fuel-air mixture preparation before induction into the combustion chamber and overall engine performance. Though past investigations have supported a well-mixed, homogeneous charge for lean operation, General Motors researchers have found that a "wetted" intake

charge with fuel droplets and possibly with bulk stratification may be optimum for lean combustion.

Spray nozzles have been investigated to study the physical state of the fuel-air mixture through laser particle field measurements of different injectors. Lewis has also been conducting manifold-flow visualization tests with the cylinder head of a TSIO-360 engine. High-speed photos taken through fiber optics have proven excellent in this diagnostic program, leading to hot performance and emission tests.

Another important series of investigations has been conducted under the high-altitude turbocharger technology program. Since aircraft are more efficient at higher altitudes, a great deal of industry interest is directed toward higher altitude capability for aircraft engines of all sizes. Turbocharging can extract more power from a given engine displacement and it can maintain that power from sea level to high altitudes. NASA initiated a program to develop a family of advanced but cost-effective turbochargers applicable to a spectrum of conventional and alternative engines, emphasizing near-term improved spark-ignition engines as the baseline.

Analysis through verification testing was planned. Garrett AiResearch and Avco Lycoming have been heavily involved in design studies for advanced turbochargers on future engines. With a Lycoming engine currently flying in the high-altitude Mooney M30 and a Continental mounted in the high-altitude Piper Malibu, both using Garrett turbochargers, the development of turbocharging appears to have entered a new era.

Advanced Concepts

Although current aircraft engines operate at high levels of efficiency and reliability, changing requirements in terms of fuel economy, fuel availability, and environmental concerns have brought about ideas for significantly improved or completely new types of engines for future aircraft. NASA has addressed the issue through a series of conceptual design study contracts with engine manufacturers that should lead to radical departures from 40-year-old design philosophies.

Over the past 50 years the spark-ignition aircraft piston engine

has proven so safe and reliable that major design changes have come slowly. Presently, this design serves as prime mover for 93 percent of the nearly 200 000 active aircraft in the general aviation fleet. Rising fuel prices coupled with the possibility of reduced fuel availability have added impetus to the search for advanced piston engines that can preserve the increasing utility of this vital segment of the U.S. transportation system.

Fuel availability surfaced as one of the more important factors involved with future engines. NASA did a thorough survey of the past, present, and future of the energy industry, not only of the technical aspects of development of primary energy sources, but also of the economic, social, and political trends that might affect choice of a future fuel. Assuming the technology to exploit such resources as oil shale and coal, the study concluded that petroleum-based fuels would be around for a long time to come.

There were two prospects identified for advanced engine fuel: continued use of 100LL avgas and kerosene-based commercial jet fuel. Low-lead 100 octane avgas, for use in the near term, dictates use of a homogeneous charge combustion system similar to that used today. For the far term the move away from specialized aviation gasoline will have to be made since it is less than 1 percent of all the gasoline produced in the United States. Future use of jet fuel suggests a stratified charge combustion system.

Stratified Charge Engines

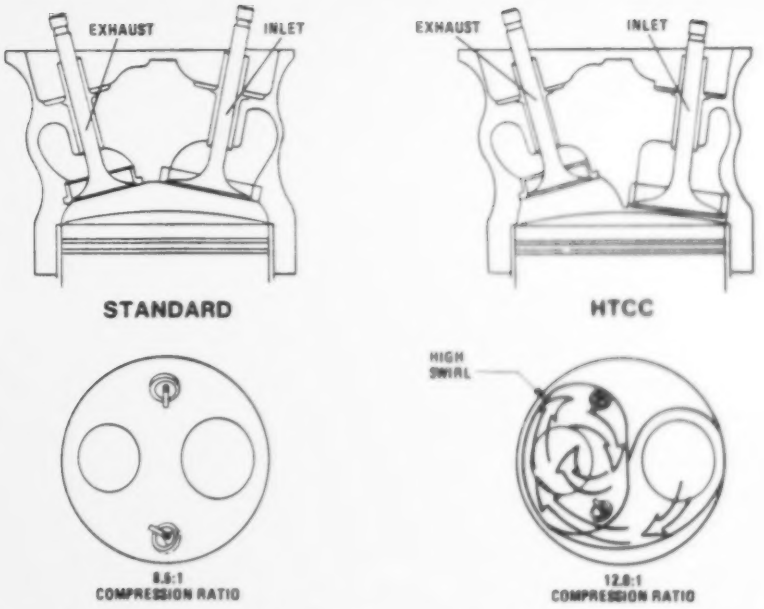
The term stratified charge refers to two levels of fuel richness in a combustion chamber. A lesser charge of a rich mixture is ignited, which then fires the remainder of a charge that is too lean to ignite easily. A longer technical description has fuel injected across an ignition source tangentially into a rapidly swirling air mass (the rotary does this by its inherent geometry). With immediate ignition assured by a positive ignition source, the fuel then proceeds to burn smoothly at a rate controlled by the fuel injection. There is then no ignition delay period and no question of knocking or detonation and there are no cetane or octane requirements. Spark plugs could very well be replaced with glow plugs, catalyst strips, or even the very hot internal surfaces of an adiabatic engine. The ultimate limit for rapid heterogeneous com-

bustion is expected to occur when the fuel as well as the air and combustion chamber surfaces are heated to a highly combustible temperature. This eliminates the physical part of the ignition process (droplet evaporation) so that the combustion rate is then controlled by mixing processes.

The two advanced engines decided on were similar with the exception of fuel and combustion system. The combustion chamber in both the moderate-risk and high-risk engines was redesigned. In the case of the former, the system used a low-pressure fuel injection system where gasoline was injected in the intake manifold just upstream of the intake valve. The high-risk stratified charge system injected jet fuel at high pressure directly into the combustion chamber just before the piston reached top dead center.

The new design was labeled HTCC or high-turbulence combustion chamber. A bathtub-shaped recess was cut into the firedeck in the exhaust valve area. A specially shaped passage leading from the intake valve area to a corner of the bathtub produced an extremely strong air swirl motion when the piston neared top dead center. This motion, combined with the HTCC's high compression ratio, resulted in high flame speeds. In effect, it became possible to ignite and burn mixtures that otherwise would be too lean to support stable combustion. The rapid burn and high initial compression of the HTCC resulted in increased peak firing pressures. With the HTCC chamber, NASA demonstrated the detonation-free operation of a homogeneous charge, 6-cylinder engine at a compression ratio of 12:1 compared with 8.5:1 for a standard engine. This increase in compression ratio had the effect of improving fuel economy at cruise powers by 7 percent. Teledyne Continental's 520-cubic-inch engine with the HTCC proved quite capable of even better performance figures with further research, leading eventually to a stratified charge version which would burn jet fuel, liquid propane gas, or alcohol.

Power can be taken in several ways from the waste exhaust gases of an internal combustion engine, among them turbocharging, as discussed earlier, and turbocompounding. NASA's advanced engines have been earmarked for both systems. Turbocompounding is not a new idea since it was used in the 3000-horsepower engines of the post-World War II era but to apply it to 350-horsepower engines constitutes advanced technology.



Primary differences between a standard compression chamber and the high turbulence version are shown here. Compression ratio and lean fuel burn are significantly increased.

In these smaller engines exhaust gases leave the engine and pass through a power turbine, which transmits power back into the engine crankshaft through a speed reduction unit. The gases then carry their remaining energy to a turbocharger, making it possible to extract one horsepower for every pound of weight added, enhancing efficiency.

Both the moderate-risk and high-risk engines will be adapted to electronic control of all operational systems. This means that the present three levers now used to control engine revolutions per minute, manifold pressure, and fuel mixture will be combined into a single lever. With the increasing amount of single-pilot instrument flying and the ever-growing complexity of the air traffic control system, this single power lever can reduce pilot work load, thus enhancing safety.

Advanced materials have been earmarked in both engines for weight reduction and increased durability. The baseline TSIO-550 represented the current level of technology with a weight of 585 pounds, while the moderate-risk 420-cubic-inch engine came down to 485 pounds, a weight reduction of 17 percent. The reduction in use of steel and aluminum was brought about by the more judicious use of these metals in conjunction with 10 pounds of advanced materials.

The high-risk engine, also 420 cubic inches, used only 80 pounds of steel, primarily in the crankshaft, reduction gears, cylinders, and exhaust valves. Aluminum was reduced somewhat and a total of 119 pounds of advanced materials was incorporated for an engine weight of 405 pounds, a 31 percent improvement over the present-day engine. In this engine the greatest part of the advanced material weight was titanium, with a small amount of reinforced plastic and ceramics.

All three engines were rated at 350 horsepower, cruising at 25 000 feet at 250 horsepower. Service ceilings of the advanced engines were increased to 35 000 feet compared with 25 000 feet for the current engine. The time between overhaul (TBO), 1400 hours on the current engine, was increased to 2000 hours for the advanced engine. To get an idea of the fuel economy improvements obtained, compare the power wasted in the exhaust of the three engines. The current technology engine dumped the equivalent of 319 horsepower out the exhaust at maximum cruise power. For the moderate-risk engine this loss was reduced by 33 percent to 214 horsepower and by 51 percent to only 156 horsepower for the high-risk engine.

The bottom line is how all this results in improved airplane performance. All three engines were simulated for installation in a current single-engine aircraft designed for the high-risk engine. The present technology engine resulted in a range of 518 nautical miles while the moderate-risk engine achieved 814 nautical miles, an increase in efficiency of 32 percent. With the high-risk engine, efficiency increased by 49 percent.

Intermittent Combustion Engines

When the Environmental Protection Agency first told the FAA it wanted improved exhaust emissions standards for general avia-

tion engines. NASA was tasked to do the research starting in 1973. By the time Avco Lycoming and Teledyne Continental, along with in-house NASA studies, came up with alternative GA engine possibilities in 1975 the fuel crunch had hit. Fuel economy and alternate fuels became the drivers for developing the engine technology.

By 1977 advanced air-cooled, spark-ignition engines, diesels, rotaries, and external combustion engines were being developed for testing, although the latter was dropped since it was very heavy. The central focus of this intermittent combustion (IC) class of engines was use of jet kerosene and similar fuels with high efficiency. By 1982 NASA dropped further aircraft gasoline engine research in favor of a horse race between turbine and IC engines to see which would come out as the most efficient. The contest has yet to be decided, if it has to be decided at all, since both types of engines have excellent futures.

Under NASA contracts, Teledyne Continental worked on an advanced spark-ignition engine of conventional configuration; Teledyne General Products came up with a compact two-stroke radial piston diesel; and Curtiss-Wright analyzed a lightweight liquid-cooled, stratified charge rotary engine.

All the IC candidates delivered improved performance when compared with current production gasoline engines and a hypothetical, highly advanced but unregenerated turboprop. The rotary and the diesel, very close in mission fuel and aircraft weight savings, provided the best overall performance with dramatic fuel/weight savings of about 43 percent. The baseline engine used avgas while the others were jet kerosene burners. Considering the differences in energy content, density, and cost between kerosene and avgas, the savings can be extended by another 10 to 15 percent for a more realistic measurement of the economic benefits.

The rotary engine emerged as the overall top-choice IC engine, with the diesel a strong second. As far as performance, the rotary had only a small advantage but predicted passenger comfort levels (based on low vibration) emerged as significant positive factors in the overall evaluation, which only the turboprop could match.

Rotary and diesel engines are also being considered for growth to supply both the GA and commuter markets. Both engines have

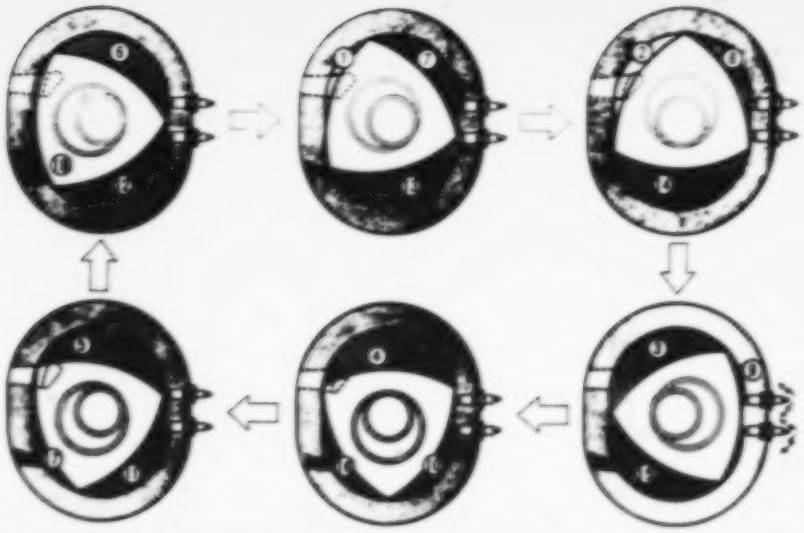
NASA has been testing rotary engines at Lewis Research Center. Here, a Mazda engine is being run with glowing exhaust pipes.

been labeled adiabatic/turbocompound or ATC in reference to the most desirable versions of these engines, which use ceramics to block most of the heat transfer that would otherwise go into the coolant and a compounding turbine to recover a portion of the thermal energy.

Automotive adiabatic (or noncooled) diesels have been under test for some time, particularly for the U.S. Army. Cummins Diesel Engine has had an Army truck on the road with a 6-cylinder engine that has no radiator, fan, water pump and tank, expansion tank, water hoses, fan belt and pulleys, air scoops or openings, and related equipment. The ceramic cylinder liners, piston crowns, firedeck, and other internal insulated components were able to contain the high-temperature combustion gases, block off most of the heat transfer to the empty cooling jackets, and direct the very hot exhaust gases to a turbocharger and compounding turbine. Though too large for aircraft application, the new technology represents a major technical breakthrough that can be incorporated into aircraft engine technology.

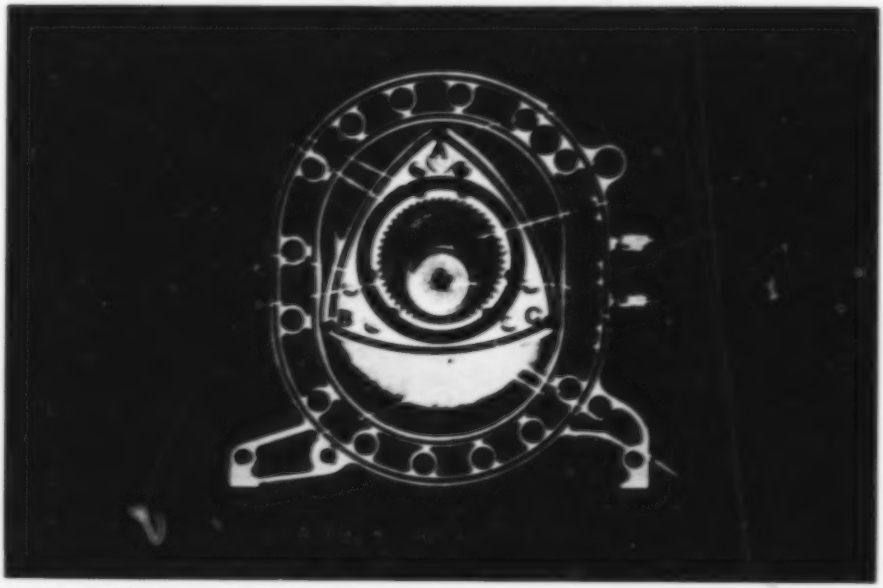
Rotary engines have finally become energy efficient. Toyo Kogyo has overcome the early rotary auto engine's excessive fuel consumption with its Mazda cars. Curtiss-Wright, under U.S. Navy/Marine Corps sponsorship, developed a large stratified charge multifuel rotary marine engine. Two fuel injectors, pilot and main, are located in the "wasp-waist" region of the trochoid housing near the top center position. The pilot injector sprays in a small amount of fuel over a high-energy multiple discharge spark plug, establishing an ignition "torch," which continuously ignites the main fuel charge as it is injected. The motion of the rotor in the trochoidal housing is such that the air motion in the injector region always proceeds in the downstream or "leading" direction. By tailoring the main injector flow to the instantaneous airflow rate past the injector station, a stationary flame front is established under the "wasp-waist." The rotor merely pushes the air through the flame front by virtue of its inherent motion and geometry. The ignition torch is energetic enough to immediately ignite any fuel than can be pumped through a diesel-type injection system.

Curtiss-Wright (C-W) developed this engine further with two-rotor and four-rotor versions. The latter 1400-cubic-inch engine



Principle of the Rotary Engine

1–4	Intake
5–9	Compression
10–12	Power
13–18	Exhaust



Rotary combustion engine basics

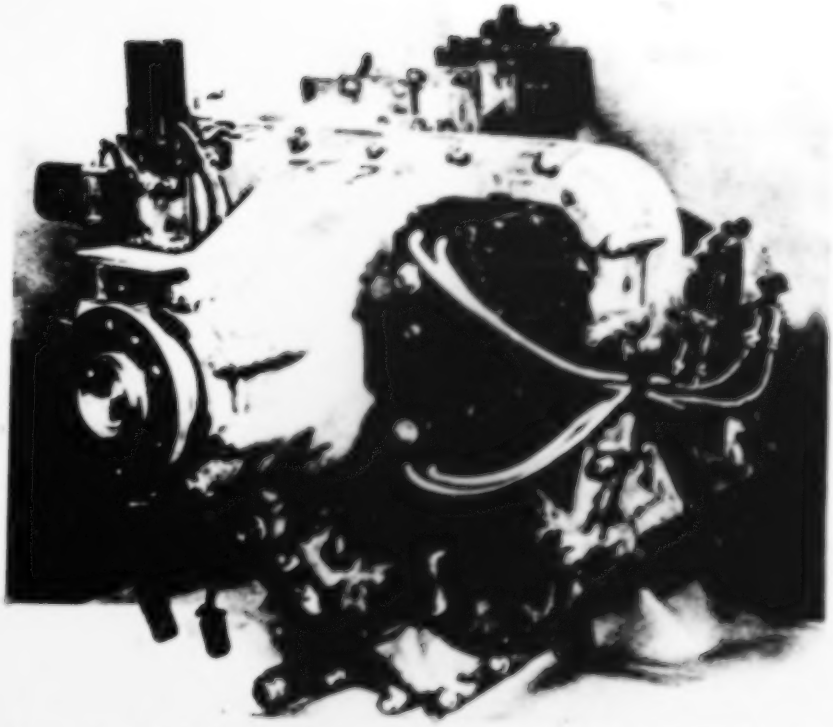
weighs under 1900 pounds and, without turbocharging, develops 1500 horsepower at only 3600 revolutions per minute. Based on C-W and NASA calculations, this power output could be more than doubled by turbocharging plus a slight increase in rotational speed. A four-rotor engine of this type could very possibly develop 4000 horsepower or more without weighing more than 2000 pounds.

Of more immediate interest is the twin-rotor version that has come to the end of a five-year development and preproduction testing program for Marine Corps use in NATO. Curtiss-Wright conducted a growth study of this engine for advanced and highly advanced versions for commuter aviation use. The technical risks were found to be no greater and no less than those for the GA rotary engine—everything was just bigger.

Taken together, the NASA GA engine studies, the Cummins adiabatic diesel truck engine results, and the Curtiss-Wright work on stratified charge rotary engines were viewed as indicating exceptionally good technical prospects for larger horsepower aircraft diesel and rotary engines. As a result, in 1981 NASA sponsored more studies of aircraft diesel and rotary engines in the 800- to 2400-horsepower class.

Teledyne General Products completed a study of the 800- to 2400-horsepower class of lightweight diesel commuter aircraft engines. While many key features remained from the GA engines, these larger engines involved higher speeds, higher loadings, and adiabatic/ceramic combustion chamber technology similar to that developed by Cummins. These power plants combine the lightweight two-stroke radial design philosophy of the GA designs with Cummins-type adiabatic components. The insulated combustion chamber greatly reduces, and may even eliminate, the coolant system head load, which should correspondingly reduce the cooling drag and provide more energy to the turbocharger and compounding turbine. This high-speed, high-pressure cycle demands substantial technology advancements, particularly in insulated combustion chamber components, high-speed, high-pressure fuel injection, high-performance turbocharger/turbocompounding, and advanced piston rings and lubes.

The resulting commuter aircraft engine is a 90-degree X-8, two-stroke, piston-ported adiabatic turbocompound of 2000



Curtiss-Wright built the RC2-75, which was test flown in a Cessna aircraft. This initiated the use of rotaries in general aviation. (Curtiss-Wright)

horsepower. Depending on whether advanced, lightweight composite materials are extensively used, the engine is projected to weigh 1350 to 1550 pounds, fitting into a 2½-by-3-by-5-foot box, making it as compact as the rotary previously discussed. Notable is the 15 000-foot cruising brake specific fuel consumption (BSFC) of 0.30 pound per brake-horsepower hour. The power plant is no larger than the Cummins truck diesel and probably no heavier, yet it develops 10 times the power, nearly equal BSFC, and all that on a full-time, 100 percent duty-cycle basis. Although the technical risks are great, the results are certainly worth pursuing.

Studies on stratified charge rotaries were conducted in parallel

with the diesel work in the same power range. Under a NASA contract, Curtiss-Wright extended its previous GA studies to the larger engine sizes, the only difference being that turbocompounding was allowed as an option. Engine definitions were based on conventional cooling and material temperatures were not increased, which, though including many advanced mechanical technologies, meant these engines have neither the benefits nor the technical risks associated with adiabatic ceramics.

As this work was going on, NASA conducted a parallel in-house study of the potential benefits of adding adiabatic uncooled operation to the Curtiss-Wright engine definitions. It was estimated that by adding ceramic or other insulative trochoid liners and rotor/end housing faces and deleting the conventional cooling system, the power recovered in the compounding turbine could be increased by 10 to 15 percent of engine total shaft power. The structural weight added for ceramic/insulative components was generally offset by eliminating the conventional coolant system.

In the end, NASA's first attempt at an adiabatic turbocompounded rotary engine amounted to improving the C-W specific weights and cruise BSFCs by 10 percent each. Subsequent comparative performance studies revealed that the conventionally cooled rotary is not competitive with a highly advanced turboprop for commuter aircraft. Looking at C-W and NASA studies together, the resulting adiabatic/turbocompound version of the rotary engine retained all the known desirable features inherent to rotary engines, with greatly extended durability a realistic possibility.

In February 1984 Curtiss-Wright, forced to close down the plant conducting rotary research, sold its rotary rights and interests to Deere & Co., which agreed to carry on the research for NASA if a suitable aircraft engine partner could be found. By March 1985 Avco Lycoming agreed to become a partner with Deere and both companies have since announced they plan to certify and market the world's first 350- to 400-horsepower Jet-A fuel-burning rotary aircraft engine by 1990. During that time period Deere assumed the NASA C-W contract to build a high-performance, multifuel rotary test engine rig and successfully completed it with the possibility of future work involving the testing of advanced components and systems.

As a result of the promise and advances in rotary research, in June 1984 NASA decided to focus future general aviation research and testing efforts in that area. A typical 80-cubic-inch displacement engine developing 200 horsepower would weigh about 250 pounds, fit inside a 16-by-50-inch cylinder, and match the BSFC of today's highly developed avgas reciprocating engines while burning Jet-A kerosene-type fuels. A highly advanced version would have true multifuel capability, an overall fuel savings of about 50 percent, and nearly twice the power output for the same size.

These developments in industry enthusiasm and commitment have pushed GA rotary engines out of limbo and into production reality. According to one of Lewis' propulsion managers, "While a great deal remains to be done, it appears that, with proper attention to advanced technologies, this novel power plant could have the most revolutionary impact on the aircraft engine business since the modern turbofan was introduced about 30 years ago. Justly, and with pride, NASA can lay claim to having had a significant and positive role in this process."

Future Developments

As in the diesels, the use of insulated (possibly ceramic) combustion chamber components results in zero or minimal coolant heat rejection and cooling drag and more energy to the compounding turbine. On the other hand, as with the diesels, the high-speed, high-pressure cycle demands significant technology advancements, although with uncertainties higher than before. Compared with the previous diesel, this is a long, cigar-shaped power plant which, in the 2000-horsepower version, would fit into a 2-foot diameter by 8-foot long cylinder. Engine weights are comparable, as well as BSFCs if one accepts the ATC cycle rotary, but the rotary is rated to cruise at 75 percent of maximum takeoff power while the diesel was rated to cruise continuously at 100 percent of its maximum power.

Aside from cruise-power applications and problematical differences in technological risk/credibility, the two engines appear to be equal in potential benefits, leading to a horse race with gas turbine core engines.

With these intriguing data in hand, NASA then did a series of in-house airplane/mission evaluation studies in which the present diesel and rotary engines were compared with each other and with a similarly advanced turboprop engine. For a 30-passenger, Mach 0.6, 20 000-foot mission with a 2400-nautical-mile design range, both the diesel and the rotary were sized considerably smaller than the turboprop because of the latter's considerably worse power lapse rate from sea level up to 20 000 feet where engine sizing occurred. Also, with 100 percent diesel and 75 percent rotary cruise power, the rotary ended up one-third larger than the diesel, with a larger base engine weight and corresponding weight differences reflected throughout the airplane.

Bearing this difference in mind, both the diesel and rotary were substantially heavier than the turboprop while consuming considerably less fuel. All three airplanes turned out to be about the same size but both the rotary and the diesel were at least competitive with the turboprop. The diesel showed a definite edge over the rotary due almost entirely to its more aggressive rating philosophy.

In essence, both the diesel and the rotary give competitive overall performance but are more economical than the turboprop. Though many elements of the direct operating cost equations have yet to be addressed, these engines simply use less fuel. In an era of true fuel scarcity, which would be entirely different from today's high fuel price scenario, they could well make the difference between continuing operations or not.

The promise of both the diesel and the rotary is great but both require four major new technology items to be completely successful, some of which are being addressed by NASA research. Despite varied applications, both require advancements in the tribology area, that is, low-friction, low-wear sealing elements and lubes to survive in a high-speed, hot, high-pressure environment. For the rotary in particular, apex seals are needed to reduce contact force or a controlled clearance liftoff condition at high speeds.

Both require at least partially insulated combustion chamber componentry to approach the benefits of the ATC cycle. For the diesel a fairly straightforward extension of the Cummins approach may do. For the rotary, however, there is no precedent at all, even though the basic intent is the same. Both require very fast fuel in-

jection and stratified charge combustion systems, a substantial problem despite reported progress in other areas. Cyclic combustion rates four to six times higher than state-of-the-art truck diesels are needed.

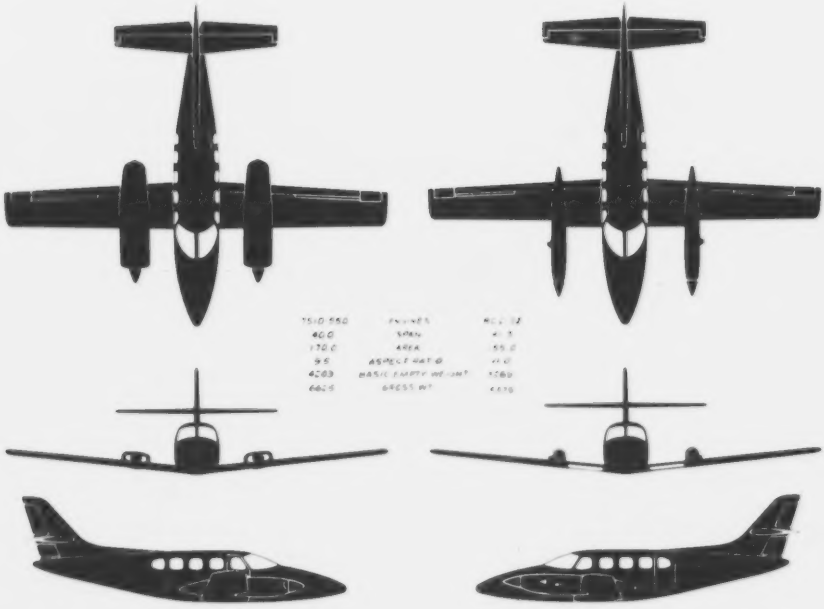
Finally, both engines require advanced turbochargers and compounding concepts. The compounding system was not considered cost-effective for the GA class of engines but is a unique requirement for the larger engines. However, such a system adds weight, cost, and reliability concerns. An alternative approach is available for four-stroke cycle engines with pressure or pneumatic compounding in which a "super turbocharger" concentrates any available excess exhaust energy into the form of higher compressor discharge pressures. With high component efficiencies it should be possible to run the compressor discharge pressure substantially higher than the turbine inlet pressure. NASA has run in-house tests on a four-stroke diesel engine with over 10 percent improvement to both power output and specific fuel consumption.

Engine/Airframe Integration

In order to help determine which of the four promising concepts for new general aviation engines of the 1990's should be considered for further research funding, NASA initiated the Advanced Aviation Comparative Engine/Airframe Integration study with Beech and Cessna Aircraft Companies. Rotary, diesel, spark-ignition, and turboprop power plants were compared against a conventional state-of-the-art piston engine as a baseline. Computer simulations of the performance of single- and twin-engine pressurized aircraft designs were used to determine how the various characteristics of each engine interacted in the design process. Comparisons were then made of how each performed relative to the others when required to fly a mission.

Evaluation of the results placed heavy emphasis on low fuel consumption and direct operating cost and on high flight efficiency. Acquisition cost, noise, multifuel capability, and ease of installation were also considered but not weighted as heavily.

Cessna's results indicated that the highly advanced rotary offers the best all-around performance and features for future general aviation aircraft. The diesel was rated only slightly lower, while the

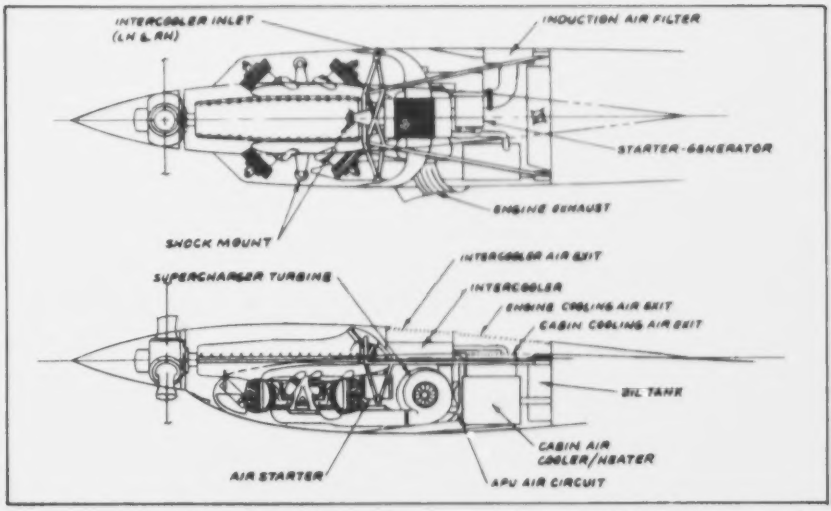


This illustration depicts a comparison of the same Cessna aircraft powered by normal piston engines and rotaries under NASA's Advanced General Aviation Comparative Engine/Airframe Integration Study.

other engines, though showing worthwhile advances, did not appear as promising. In particular, the turboprop was viewed primarily as a viable replacement for the baseline engine, offering market appeal rather than large improvements in efficiency or cost. Regardless of the assumptions made (drag level, weights, cost, etc.) and missions chosen, the results proved the same while advanced materials and aerodynamic features, combined with advanced engines, offered substantial gains in performance, fuel burn, and cost.

Beech came up with basically the same results. The highly advanced rotary offered low weight and fuel consumption as well as small size, making it ideal for aircraft use. The other advanced engines offered improvements that were only slightly less dramatic when compared to the rotary.

Both manufacturers recommended that NASA consider



This is what a highly advanced diesel engine installation could look like in a twin-engine general aviation aircraft. As with the rotary, the frontal area is drastically reduced while performance gains are significant enough to merit further investigation.

developing the technologies required by all the advanced engines in common and allow the individual manufacturers to apply the technologies to their designs rather than invest in the development of a single engine type. This could foster competition among the engine manufacturers and provide a wider range of engine options for the 1990's.

The pioneering engine programs mentioned here need to continue, though they are often the first to fall to the budget axe. Developmental research could provide the next great breakthrough in leaving World War II technology behind and reaching out to the future.

CHAPTER 4

TURBINE ENGINES

When NASA began to study general aviation potential, it started with turbine engines because of the large base of contemporary research being performed. In early 1977 four independent studies were contracted by NASA for a future small, general aviation turbine engine (GATE) ranging from 300 to 600 horsepower with improvements in specific fuel consumption (SFC) of 20 percent and engine cost savings of 40 percent.

Generally the turbine engine has been accepted as the most desirable type of power plant because of its very low vibration levels, high reliability, multifuel capability, better safety record, low weight, fewer exhaust emissions, less maintenance, and smaller installation losses. However, turbine engines have been limited to above the 500-horsepower range due to higher fuel consumption and a 3 to 1 price differential when compared with low-horsepower reciprocating engines. The challenge, of course, is to overcome the cost and fuel barriers without sacrificing the superior qualities. Current technology does not allow this.

NASA wanted to emphasize technologies that had high payoff and low risk, but which could be ready for production development by 1988, assuming sufficient funding. A market forecast was undertaken, considering all types of small aircraft and helicopters, then optimum engine configurations for each important mission were evaluated. Anticipating that the marketplace could not afford different optimum engines for each application, an evaluation

NASA has conducted design studies, such as this one, for a propfan-powered executive transport.

was made of a single common core to be used in a family of engines. Lastly, the required research and technology program was defined.

As Garrett AiResearch, Detroit Diesel Allison, Teledyne Continental, and Williams Research worked with and for NASA, all four companies came to independent conclusions that turboprops instead of turbofans or turboshafts offered more promise. When trying to lower cost of a turbine, efficiency suffered, but the challenge was either to develop advanced technology that could improve performance without cost increases or to design a cost-effective unit. In the end, three study teams pursued the low-cost turbine versus piston theme while the fourth concentrated on a

high-performance, advanced turbine versus current turbine theme.

Design turbine-inlet temperatures were optimized at 2200° F, or about 400° F above current small engine levels. Cost was about 40 percent cheaper since physical size was about 40 percent smaller and more cost-reducing technology was incorporated. Fuel consumption was improved 15 percent due to the weight reduction, not cycle efficiency. As a matter of fact, the small airflows were not conducive to improved cycle efficiency and even resulted in increased fuel consumption. However, engine weight and cost savings also produced 15 to 20 percent improvements in airplane acquisition cost, operating cost, and total cost of ownership.

The four companies settled on turboprops ranging from 335 to 565 horsepower, aimed primarily at the high-performance single-engine and twin-engine aircraft market. Engine cost improvements were predicted through a number of technologies, including use of powdered-metal gears and laser hardening in the gearbox, composite material or die-cast aluminum gear cases, composite drive shafts, and full authority digital controls. The key elements in all the concepts involved the rotating machinery: high-performance centrifugal compressors using advanced analysis techniques, some form of passive clearance control, and backward curvature. High-stage loadings without severe performance penalties were prevalent as well as new manufacturing processes.

The common core concept for reducing engine cost was essential to the project. Retaining parts commonality without sacrificing too much performance was the key because each of the diverse mission applications preferred a different optimum engine. For example, a 335-horsepower engine grew 70 percent to a 565-horsepower derivative with a 4-inch extension, a 31-pound weight increase, and a 54 percent increase in cost. At the same time, the SFC was 10 percent lower because of the increased cycle temperature and pressure and component rematching. The price of commonality was a 2 percent SFC penalty for the basic core engine. However, the benefits were a 7 percent lower cost and a 16 percent weight reduction.

GATE technology advances were theoretically applied to twin-

turboprop airplanes, resulting in cost reductions of 15 to 25 percent and operational savings of 30 to 40 percent when compared to their piston-powered counterparts. However, the benefits for high performance were only one-third to one-half as much. When the GATE program ended around 1980 the door was open for large improvements in aircraft economies at the upper end of the reciprocating-power class. It also filled the gap between the relatively inexpensive reciprocating aircraft and the expensive turboprop aircraft, bringing the many other virtues of turbine engines to a wider spectrum of users and applications.

When applied to commuter aircraft, advanced turboprop engines and propellers offer 15 to 20 percent fuel savings and 10 to 15 percent reductions in direct operating costs compared with the new crop of 1500- to 2000-horsepower engines currently in development. Unconventional engines could boost fuel savings to 40 percent. NASA sponsored a series of future advanced turboprop studies with Detroit Diesel Allison, General Electric, and Garrett Turbine Engine for engines ranging from 1500 horsepower for a 30-passenger, Mach 0.45 twin-engine airplane, to 4800 horsepower for a 50-passenger, Mach 0.70 twin designed for both executive travel and commuter service. Component improvements were earmarked in compressors, turbines, combustors, controls, gearboxes, shafts, bearings and seals, accessories—virtually every major area.

The smaller commuter aircraft use GA-type propellers that are relatively simple with overall lower performance compared to the more sophisticated technology applied to larger commuter aircraft. These lower cost propellers are typically constructed with solid aluminum blades having circular shanks, which contribute to lower thrust efficiency. The newer, more sophisticated propellers utilize such weight-saving construction techniques as aluminum spar-fiberglass shell blades and such performance improvements as airfoil shanks, advanced airfoils, and low activity factors.

Even with the relatively high propeller efficiency of 0.87, technology studies by Hamilton Standard, the McCauley Division of Cessna, and Purdue University have identified further opportunities. Proplets or biblades could increase efficiency nearly 2 percent through reduced tip losses. Advanced materials could reduce fuel consumption about 1 percent through weight savings

or from the ability to use more blades while maintaining sufficient blade retention strength in the thinner root sections. This permits more efficient, lightly loaded blades with activity factors about 70 compared with currently limiting values of 90 to 95. These blades could be constructed, for example, with a steel or metal matrix spar with a Kevlar or graphite shell. The shell could be load sharing, unlike current designs, and the blade specially tailored to avoid aeroelastic flutter problems at high propeller speeds. Fatigue life and maintenance costs must be considered in an overall evaluation of these new designs.

Another attractive concept is synchrophasing the left and right propellers to within a technically challenging one degree in phase angle. Experimental evidence indicates that an 8-decibel noise reduction potential exists for precision synchrophasing, which could eliminate large fuselage acoustic weight penalties for typical wing-mounted engine configurations. That amounts to 800 pounds or more for a 30-passenger, Mach 0.45 airplane with Boeing 737 cabin noise level.

Advanced Gas Turbine

The problems involved in designing and building small turbine engines remain difficult to solve since much turbine work is generic in nature. Small turbine research at NASA began in the 1960's but the small rocket engine turbopumps and auxiliary power units involved were nothing like the general aviation turbines. NASA's small turbine research is concerned primarily with aerodynamic performance and turbine cooling in both radial and axial turbines. Though much of current advanced gas turbine research has been centered around automotive engines, the applications to general aviation are extensive.

The low-cost turbine work conducted from 1970 to 1975 was directly applicable to GA engines, leading to an understanding of the influences of such things as rotor tip clearance, turbine and stator blade design, blade aerodynamics, and other factors affecting small turbines. Several analysis methods were formulated with computer codes for axial and radial turbines as well as channel flow analysis codes. Rotorcraft engine work also was initiated at Lewis.

By the mid-1970's the term advanced gas turbine (AGT) sur-

faced in reference to a very small high-work axial or radial turbine of very simple design with no cooling and extensive use of ceramic materials. An understanding of the cooling effects on performance had been studied for large turbines and much of this research was applied to the newer AGT work.

By October 1979, NASA contracted with two engine companies to build and test advanced gas turbines for automobiles with fallout applications for general aviation. Detroit Diesel Allison teamed with Pontiac while Garrett teamed with Ford to develop turbine engines that would get over 42 miles per gallon on multiple fuels in a 3000-pound car with exhaust emissions within federal standards set for 1985. Costs would have to be competitive along with reliability, low noise, and safety held within federal parameters.

This high-risk project had two evolving technologies that would significantly affect success: development of affordable ceramic components to permit higher gas turbine operating temperatures and development of small-engine-size aerodynamic components.

The AGT was chosen for development in part because of the Ceramic Applications in Turbine Engines (CATE) program, which was contracted under Lewis in July 1976. CATE applied ceramic components in an Allison GT 404-4 highway vehicle gas turbine engine, reducing fuel consumption by improving engine cycle efficiency due to operation at higher temperatures, from 1900° to 2070° F. Since ceramics are brittle, NASA and Allison engineers had to establish a level of understanding comparable to that which five or six decades of experience with metals have afforded industry.

This understanding grew from the ceramic material itself: the powders used, the process of generating complex shapes with acceptable strength, quality control, nondestructive inspection of components, cost-effective machining techniques, assessment of thermal and chemical stability, and methods of handling the brittle components without damage. Nozzle vanes, turbine tip shrouds regenerator discs, and turbine blades were tested successfully in both the 1900° and 2070° F engine configurations, paving the way for major industry/government research into large-scale use of ceramics. Use of these components can provide a turbine engine with 30 percent improvement in fuel economy over

projected 1985 spark-ignition engines and offer significant improvement beyond that with further research. The Japanese are pursuing the use of ceramics in engine components with great vigor.

Both Allison and Garrett faced major challenges in addition to ceramics development. A small turbine poses unique technical problems not encountered in larger engines due to high surface area to volume ratios for liners and domes, very small fuel injection passages subject to clogging and difficult to maintain, small passages which accentuate boundary layer, and end wall effects and complicated flow fields.

Engine applications also dictate combustor orientations. Large, advanced combustion systems are all of the axial, straight-through type while small combustors for rotorcraft, commuter, or general aviation aircraft can be reverse flow, axial straight-through or reverse flow axial and radial overflow or inflow. Since smaller engines have SFC levels well below those of larger engines, substantial improvement has to be made for the advanced cycle needs. In addition, small engine manufacturers are generally not as well equipped to meet the challenges because of lack of component facilities, particularly high-temperature and pressure capabilities, and smaller technical staffs. NASA's involvement proved crucial to providing the impetus and management for AGT research.

Through 1983 both AGT engine projects and NASA's own research program at Lewis had made significant contributions in component improvement, combustor development, advanced liners, fuel effects, fuel injectors, rotor clearances, aerodynamic flow, computer analysis, laser measurement of gas velocities, ceramics, and other areas. Both Allison and Garrett had tested portions of their engines with progress toward full-scale testing of the actual power plants. Through the 1980's the AGT program will pave the way toward efficient small turbine engines for general aviation use.

Quiet, Clean General Aviation Turbofan

The fastest growing portion of general aviation is the turbofan powered executive jet fleet. The worldwide fleet of around 5200

executive jet aircraft is expected to expand, particularly in view of the fact that in spite of GA production line shutdowns in 1982 and 1983 the jet lines continued to roll.

NASA's QCGAT (Quiet, Clean General Aviation Turbofan) program was initiated in April 1975 to improve the environmental characteristics of civil aircraft near suburban airports. This was NASA's first application of large engine technology to small engines in the general aviation or small engine field, conducted in two phases.

The initial study phase examined the applicability of current large turbofan technology to small engines, produced a preliminary design of the QCGAT engine, and developed requirements and program plan for the experimental phase. The objective of the latter phase was to demonstrate that the application of large turbofan engine technology to small, GA turbofans could result in less noise, lower emissions, and acceptable fuel consumption. Though the latter two goals were important, the program was primarily directed toward low noise. Among NASA programs that led the way in QCGAT research were QCSEE, Quite Engine, Quiet Nacelle, Refan, and Clean Combustor.

During the study phase, which lasted six months, Garrett AiResearch, Avco Lycoming, and General Electric defined the engine. Then a competitive procurement was held with contracts going to AiResearch and Avco Lycoming to design, build, and test an engine.

Each contractor approached the project by using an existing modern gas generator or engine core to save development time and money. The engine was to develop less than 5000 pounds of static thrust, and all rotating parts were to be flight worthy. A boiler plate rather than a flight worthy nacelle was acceptable. However, the internal aerodynamic contours and the acoustic treatment for the nacelle had to be of flight design.

The emissions goals selected were the now-abandoned 1979 EPA standards for Class T1 engines and NASA set its own noise goals. Since existing gas generators were being used, drastic reductions in fuel consumption could not be expected, though efficiency was not to suffer at the expense of reducing noise and pollution. Therefore, a fuel consumption goal equal to or better

than existing engines was set. Each contractor synthesized a twin-engine aircraft for their engine to get standardized noise calculations. Both engines were then to be delivered to NASA Lewis for further experimental testing.

NASA's noise goals during takeoff and approach, as well as sideline noise, were well below those set in Federal Aviation Regulation 36. As a matter of fact, four of the quietest jets flying, the Cessna Citation, Falcon 10, Learjet 36, and A300B, were selected for comparison and the NASA goal was 8 to 12 EPN decibels below any GA aircraft flying. In the range of aircraft gross weight used in the QCGAT program, the NASA goal was 16 to 19 EPN decibels below the 1977 FAA rule.

These goals were set to ensure the inclusion of existing low-noise technology in the QCGAT designs, resulting in aircraft noise levels that are perceived to be 45 to 55 percent less noisy than the levels of the quietest current business jets. Another way of illustrating the effect of achieving these goals is by using noise footprint areas or the area below the aircraft which is subject to a noise level greater than a given level during takeoff and landing. The footprint area for an aircraft using the QCGAT engines is predicted to be one-tenth that of the quietest business jets. Essentially, achievement of the stringent QCGAT noise goals could eliminate noise as a major constraint on the future growth of the turbofan-powered general aviation fleet. In addition, the abandoned 1979 EPA emissions goals were kept for the QCGAT program.

Garrett AiResearch used the core of one of their Model TFE731-3 engines, then adapted several unique components such as fan, gearbox, combustor, low-pressure turbine, and associated structures. These components formed the basis for meeting the main program objective demonstrating the application of large turbofan engine design, emissions, and noise technology in small general aviation turbofans.

A workhorse nacelle incorporating interchangeable acoustic and hardwall duct liners showed that large engine attenuation technology could be applied to small propulsion engines. The application of a mixer compound nozzle demonstrated both performance and noise advantages. Major noise reduction, beyond

that of an already quiet engine, was obtained, making the AiResearch QCGAT engine significantly quieter than any other business jet engine. The engine met design goals for thrust and emissions with slightly better reliability and performance than predicted.

Avco Lycoming met the primary QCGAT objectives with its engine and nacelle designs. They also found that large engine noise reduction technology could be successfully employed to the GA-size engine, demonstrating QCGAT acoustic goals with margin. The emissions goals were basically achieved with considerable margin for both carbon monoxide and unburned hydrocarbon (UHC) emissions and nitrogen oxide within 1 percent of the goal.

A fan module was developed around an existing turboshaft engine. The fan was designed using the latest in large engine noise control technology and a mixer was added to reduce the already low exhaust gas velocity. A nacelle incorporating sound treatment was provided. The bottom line came to significant noise control without a performance penalty.

Comparing the two engines, the AiResearch power plant was a higher thrust machine designed for an aircraft that cruises at high speed and altitude with long range. The Avco engine was a low-thrust unit designed for an aircraft that cruises lower and slower at intermediate range.

The Avco engine was applied to an advanced Beech design while the AiResearch engine was synthesized for a stretched version of the Learjet 35. A comparison of the two QCGAT aircraft was made with similar existing aircraft. The Avco/Beech performed a similar mission to the Cessna Citation I, and even though it was a much lighter aircraft, it had both a higher maximum payload capability and a lower fuel consumption at comparable cruise conditions. The AiResearch/Lear had a larger passenger or payload capability than the Learjet 35 along with lower fuel consumption at comparable cruise conditions.

The NASA QCGAT program objectives were met, demonstrating that the application of large turbofan engine technology to small GA turbofan engines can achieve low noise, low emissions, and acceptable fuel consumption.

Noise

High-speed turboprop noise also has been a part of the advanced turboprop or propfan program. The new propeller configurations, involving very thin, multiple swept blades, provide lower noise and increased efficiency at high speeds. Research into advanced fuselage treatment for aircraft with high exterior fuselage noise levels is being conducted to ensure that future turboprop aircraft have an acceptable cabin environment.

Lockheed was contracted by NASA for propfan noise work. A monocoque section fuselage 15 feet long from a wrecked Swearingen Metro was used for extensive noise experiments. Double sidewalls were found to be significant noise reducers compared to conventional aircraft fuselage sidewall construction.

More recently, Lord conducted a fuselage test with Swearingen to demonstrate active control of interior aircraft noise. A Metro II fuselage was subjected to a series of tests using real or simulated propeller noise. Then input and output transducers were mounted to reproduce the noise 180 degrees out of phase to cancel out the noise. Basically, propeller noise is detected and loudspeakers under the fuselage floor produce phase-reversed counter noise.

Though this research is still continuing, researchers believe there is good potential for the concept working since a 20-decibel noise attenuation has been achieved with the possibility of 40 decibels in the 20- to 500-Hertz range. This could very well lead to a reduced amount of passive acoustical materials for noise reduction.

Propeller tip devices have been investigated as well for both improving performance and reducing noise. Proplets, like winglets on aircraft wings, improve aerodynamic efficiency by reducing the total induced drag. An extension of the proplet concept that reduces structural loads is the bibladed propeller.

The proplet increases low-speed (130-knot) power and thrust for a 1 percent cruise efficiency improvement and a 4- to 5-percent climb performance increase. With a baseline propeller noise of 97.6 decibels, a 10-degree swept back proplet dropped the noise level by 0.3 decibel. Sweeping the proplet back 20 degrees did not reduce the noise level any further while sweeping it forward resulted in increased noise. The unswept proplet had 0.4 decibel

Fairchild Aircraft and Lord have undertaken a NASA study for noise cancellation in a Metro commuter airliner, shown here. Noise inside and outside of turboprop commuter transports remains a target for improvement. (Fairchild Aircraft)

less noise than the corresponding unswept GA blade. Reducing the diameter of a propeller and adding a tip device to maintain constant aerodynamic efficiency can result in noise reduction due to reduced tip Mach number.

Turbine engine development will remain an important area of research and testing, though NASA has selected the rotary engine as the major focus of future NASA efforts for general aviation.

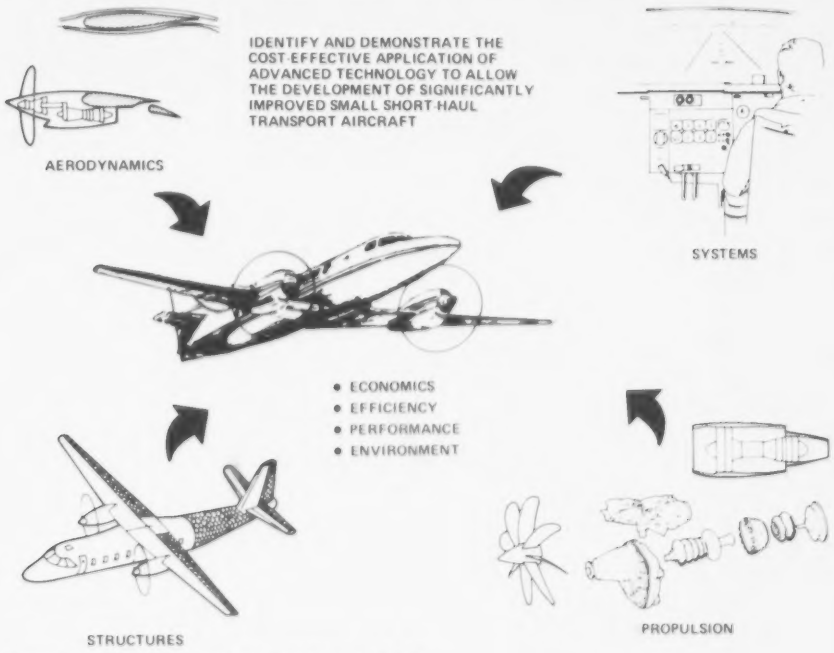
CHAPTER 5

COMMUTER AVIATION

With airline deregulation there has been a scramble for the more lucrative markets in air carrier operations. Out of this milieu, commuter or regional lines have emerged as potentially profitable and very active, feeding passengers from smaller cities to the major hub airports in aircraft seating 15 to 60 passengers. Commuter airline traffic grew from 4.3 million passengers and 43.5 million tons of cargo in 1970 to an estimated 15.5 million passengers and 500 million tons of cargo in 1980. These smaller airlines conduct one-third of all scheduled airline flights. Many larger airlines abandoned short-haul routes because they were not able to operate larger jetliners at a profit. Commuter (regional) airlines have picked up these routes using smaller, lower performance, propeller-driven aircraft, but these aircraft represent an older technology level much in need of redesign.

Small Transport Aircraft Technology

In 1978, NASA established a small transport aircraft technology (STAT) team to study whether or not there are technical improvements in commuter aircraft that would likely increase their public acceptance and use, and to examine the possibility that NASA's aeronautical research and technology program could help U.S. commuter aircraft manufacturers develop superior future aircraft. This was particularly important since there was an apparent lack of U.S.-built commuter aircraft to meet market need. Companies in Spain, Brazil, Israel, Ireland, Britain, Holland, Canada,



Small transport aircraft technology (STAT)

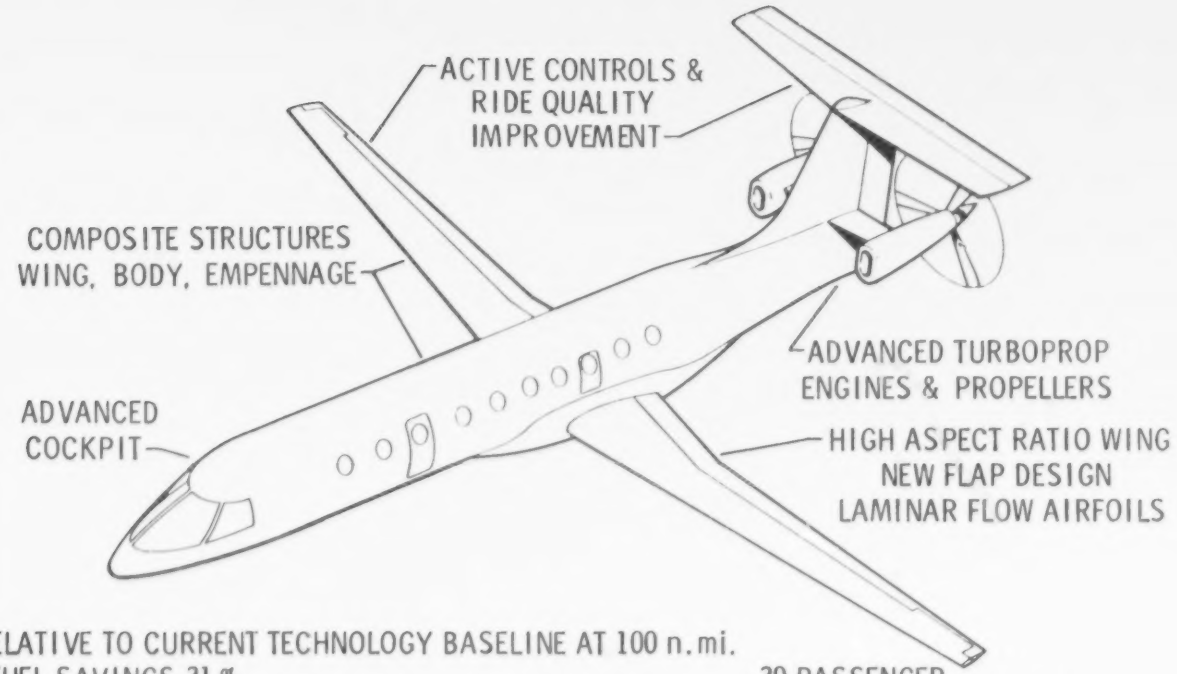
France, Italy, and West Germany have aggressively pushed forward with new designs, often with direct government monetary support. On the whole, U.S. companies are finding it hard to challenge this impressive foreign lead but at least six American firms are pressing ahead with development of new or modified commuter transport aircraft. Part of the reason for this is that the smaller manufacturers do not have the large engineering departments of the airline transport companies.

The STAT effort has been directed at allowing the American aircraft industry to develop small future transports with significantly improved economics, performance, efficiency, and environmental compatibility. The airframe, engine, and propeller manufacturers participating in these studies were Beech, Cessna, Pilatus, General Dynamics-Convair, Lockheed-California, Garrett Turbine, General Electric, Detroit Diesel Allison, Hamilton Standard, and McCauley. Current technology aircraft were used as baselines with which to compare advanced technologies to determine the poten-

This is Cessna Aircraft's design study for an advanced technology small transport aircraft.

tial for improving aircraft performance and operational economics after 1985.

In examining commuter/regional airlines, NASA found that over three-fourths of the aircraft flown by local service airlines were jet powered with passenger capacities above 100 passengers. At stage lengths of less than 500 miles, the two- and three-engine B-737, DC-9, BAC-111, and B-727 account for over 87 percent of U.S. jet transport fuel usage. This was tolerable when fuel was very cheap, but from 1973 to 1981 the average price of a gallon of jet fuel increased from 13 cents to more than $1.03. For aircraft such as the B-727-200 this drove fuel from 25 percent of the direct operating cost (DOC) to over 50 percent. More efficient turboprop and piston commuter aircraft are ideally suited to take over these routes from the larger jets since they use 20 percent less fuel per



RELATIVE TO CURRENT TECHNOLOGY BASELINE AT 100 n. mi.
FUEL SAVINGS 31 %
DIRECT OPERATING COST SAVINGS AT $1/gal 24 %

30 PASSENGER
CRUISE SPEED = 0.5 MACH

This is Lockheed-California's advanced technology small transport aircraft design.

seat mile, but advanced commuter aircraft could result in significantly greater savings.

STAT studies by Cessna, Convair, and Lockheed investigated new small transport aircraft designs with 19-, 30-, and 50-seat capacity with a 600-nautical-mile range and optimized for minimum DOC over a 100-nautical-mile stage length. Additional design goals included a 4000-foot field length and passenger comfort levels equivalent to large jet transports.

Cessna's 19- and 30-passenger designs utilized structural bonding and composites in primary and secondary structures along with advanced engines, propellers, and aerodynamics. The result was aircraft that used around 40 percent less fuel (a 21 percent reduction in DOC) on a 100-nautical-mile trip.

All the Convair aircraft were designed for cruise at 250 knots and the 30-passenger design incorporated a new high-lift, low-drag airfoil, composites, active controls, and improved propellers and engines. The design ended up 22 percent lighter with 51 percent less wing area, requiring 37 percent less horsepower and using 31 percent less fuel (a 24 percent reduction in DOC) on a 100-nautical-mile trip. With rear-mounted engines, cabin noise was predicted to be significantly lower.

Lockheed placed major emphasis on reducing airframe manufacturing costs using both aluminum and composite materials. For a 30-passenger design with an improved high-lift, low-drag wing, active controls, and propulsion system improvements, the result was a 25 percent structural cost savings relative to conventional aluminum skin-stringer design. On a 100-nautical-mile trip, the rear-engine Lockheed design used 26 percent less fuel (a 16 percent reduction in DOC).

Beech applied advanced technology engines, propellers, surface coatings, and composites in the wing and empennage to one of their near-term 19-passenger designs with the same fuselage and mission requirements. On a 100-nautical-mile trip the design used 34 percent less fuel (a 21 percent reduction in DOC) but with a 17 percent higher acquisition cost.

Pilatus Britten-Norman also examined the application of advanced technologies to its current 16-passenger Trislander but found little growth potential. The firm then proposed an advanced 19-passenger design with improved passenger accommodations,

32 percent increase in cruise speed, 100 percent increase in range, lower external noise level, and 40 percent lower DOC per seat mile than the Trislander.

Though the above companies assumed rather than calculated improved propulsion, the validity of these assumptions was born out by the engine and propeller manufacturers.

Engines and Propellers

General Electric identified a dozen candidate advanced 1500- to 2500-shaft-horsepower turboprop technologies that could improve engine efficiency 14 percent and reduce engine weight relative to the CT7, a 1600-shaft-horsepower-class engine still in development. GE managed the boost through increased component efficiencies and higher cycle pressures and temperatures—as high as 20:1 and 2400° F. The compressor incorporated several aerodynamic improvements; there were thermal barrier combustor coatings for increased durability, more effective turbine blade cooling, reduced turbine running clearances, and digital controls.

Detroit Diesel Allison studied both 2400- and 4800-shaft-horsepower engines suitable for 50-passenger aircraft designed for Mach 0.45 and 0.70, respectively. In both cases the baseline engine was a scaled version of the 8000-shaft-horsepower XT701 turboprop. Using DOC as the central issue, Allison raised the compressor pressure ratio from 12.5 to 20 while maintaining the same 2500° F turbine temperatures on both engines. An efficiency gain of 17 to 19 percent, a weight reduction of 13 to 25 percent, reduced costs of 16 to 19 percent, and a reduction in maintenance costs of 56 to 62 percent resulted. With a 100-nautical-mile mission, 10 to 22 percent less fuel was used with 13 to 16 percent DOC savings.

Garrett examined power plants for 30- and 50-passenger Mach 0.45 aircraft requiring 1800- to 2500-shaft-horsepower engines. Pressure ratio would be upped to 15:1 or 20:1, which would increase efficiency 3 percent but also raise engine cost 20 percent. With several other features and general aerodynamic improvement to permit higher pressure ratios, a 13 to 14 percent engine

efficiency improvement and a 22 to 32 percent weight reduction was realized relative to scaled versions of the newer 1000-shaft-horsepower TPE331-11 engine.

Hamilton Standard defined advanced propeller technologies and associated benefits for the 30-passenger, Mach 0.45 Convair and the 50-passenger, Mach 0.7 Lockheed airplanes. The analysis concluded that for both aircraft, a six-bladed propeller with lightweight composite construction, advanced airfoils, tip proplets similar to winglets, and an advanced precision synchrophaser are required to increase efficiency and lower cabin noise. The Mach 0.45 design employed straight but extremely narrow blades, whereas the Mach 0.7 design used wide, thin blades swept 45 degrees at the tip. Both props would be 5 to 6 percent more efficient than the best of today's propellers due to advanced materials and construction techniques that permit narrower and thinner blades, and tip loss alleviation with proplets. For low-speed aircraft with tail-mounted engines these improvements resulted in an 8 percent fuel savings (a 3 percent DOC reduction). For wing-mounted power plants, these values increased to 13 percent and 6 percent, respectively, because a large acoustic treatment weight penalty required in the baseline to achieve a Boeing 727 cabin noise level was eliminated.

McCauley looked at propeller technology for a 19-passenger, Mach 0.45 aircraft. Using advanced aerodynamics, materials, and structural concepts similar to Hamilton Standard, the projected efficiency improvement would be 8 to 9 percent relative to typical general aviation propellers. Fuel and DOC payoffs similar to the Hamilton Standard results were realized.

Teledyne Continental and Curtiss-Wright undertook studies on very advanced rotary and diesel engines as alternative power plants to conventional turboprops. These intermittent combustion engines feature multifuel, stratified charge combustion systems, high-pressure ratio turbochargers (five to nine), high-speed fuel injection technology, and low heat-loss cylinders. Competitive fuel consumption was evident along with the capability of operating on jet fuel rather than avgas. More study is needed to gain a total assessment of these engines and of unconventional turboprop cycles (e.g., with regeneration).

Aerodynamics

With natural laminar flow airfoil glove tests on an F-111, significant laminar flow was evident at off-design cruise conditions of Mach number and leading-edge sweep, the region of interest for small transports. Research is also being conducted to develop airfoil designs with improved maximum lift and climb characteristics. A handbook resulted on upper-surface airfoil-contour modifications designed to improve the maximum lift coefficients, thus improving the stall characteristics of many small transport aircraft that today use NACA six-series airfoil sections. Such modifications may be used for possible retrofit on existing aircraft or in the design of new aircraft.

To establish an aerodynamic data base representative of current commuter aircraft technology, unpowered and powered small transport aircraft wind tunnel tests of a 15 percent scale model of the Swearingen Metro transport were conducted at Ames under a cooperative research agreement with Swearingen Aviation. Unpowered tests in the Ames 12-foot pressure wind tunnel investigated aircraft component drag buildup, while powered propeller tests investigated the effects of propeller slipstream on wing aerodynamic characteristics.

Most of NASA's general aviation research can be applied to small transports, including flight control systems, navigation and guidance systems, cockpit displays (see chapter 8), and other aircraft subsystems such as icing protection (see chapter 7). These systems are very important to the overall success of the aircraft design, including aircraft performance, passenger comfort, safety, and economics.

The overall conclusion of the STAT airframe, engine, and propeller studies is that very significant improvements in energy efficiency, operating cost, and passenger comfort are possible for future small transport aircraft through combined advances in all the aircraft disciplines. In many ways, the technologies studied depend on each other for the maximum benefits.

A NASA ad hoc Advisory Subcommittee on Commuter Air Transport Technology comprised of government, university, and airline, airframe, engine, and propeller industry representatives recommended that NASA undertake an aggressive research pro-

Another advanced configuration small transport under wind tunnel test by NASA shows a canard (forward) wing, pusher props, advanced aerodynamics, and relaxed stability for active controls.

gram to quickly bring the specialized small transport technologies to a state of readiness for commercial development by 1985.

The overall goal of this research would be the establishment of technology readiness enabling the following future commuter airplane improvements:

Direct operating cost reductions of 20 percent
Fuel savings of 35 percent
Increased reliability and safety
Boeing 727 level of passenger comfort
Reduced maintenance

Many other recommendations were made for further research not being done in the transport or general aviation areas. Engine and propeller technology needs emphasis since commuters fall between the larger transports and the smaller general aviation aircraft. A unique problem in commuter operations is the severe duty cycle (rapid changes from idle to takeoff power to cruise to landing) imposed on commuter engines. Ultimately, new engines designed specifically for this mission will have to be built. Ride quality improvement through active control gust alleviation is another area of importance; not only would it provide more comfort for the passengers, it would also reduce pilot work load and reduce wing structural fatigue. This is particularly significant for commuter aircraft since they operate routinely at low altitudes and with lower wing loadings than large transport aircraft.

The STAT studies explored all areas in which advanced technology application could improve passenger acceptance, safety, operating costs, and profitability with 19- to 50-passenger aircraft. While available technology could improve future commuter aircraft, the synergistic combinations of advances in aerodynamics, propulsion, configuration design, and aircraft systems could reduce fuel costs up to 40 percent, direct operating costs up to 24 percent, and aircraft acquisition cost by as much as 18 percent along with improvements in passenger comfort and convenience.

CHAPTER 6

GENERAL AVIATION UTILITY

In addition to the more revolutionary developments in NASA's general aviation research, avenues are being investigated to increase the utility of the general aviation environment. How can the usefulness of certain aspects of commercial and non-commercial GA flying be enhanced and developed? NASA's efforts have centered around improvements for the air traffic control (ATC) system in which all aircraft operate, and research into agricultural applications and aerial spraying.

Air Traffic Control

The safe, efficient, and dependable flow of air traffic represents a major challenge for the ATC system. Moving traffic under instrument flight rules (IFR) is already a serious problem, and with aircraft operations projected to double by the mid-1990's, airport congestion will reach an alarming condition. With the exception of small private fields, no new airports have been built in the U.S. since 1970 because of cost, urban congestion, and a host of other factors. Clearly, maximum use must be made of our air space and existing airports.

The Federal Aviation Administration (FAA) has an extensive program for developing an improved ATC system. The two-way data link associated with the discrete address beacon system (DABS), scheduled to become operational in the late 1980's, will provide the vital missing element required for a quantum jump in advanced operating procedures. DABS will be capable of uplinking many services to aircraft equipped with electronic displays and

appropriate input-output devices. Eventually, these services would augment voice communications with alphanumeric messages to provide altitude assignment, weather data, and runway conditions. DABS may be used to uplink holding instructions, approach and departure clearances, and metering and space commands. It also may be used to transmit data for cockpit display of traffic information (CDTI). Ultimately, it may relay traffic-time-sequencing data needed for driving "time-boxes" in cockpit displays for precise space and time (4-dimensional) navigation from takeoff to landing.

Important to terminal area operations will be the navigational capability provided by the microwave landing system (MLS) slated for initial implementation in the mid-1980's. The MLS will permit high-precision guidance commands to be generated for following trajectories optimized for energy efficiency, noise reduction, and airport capacity. A revolutionary possibility for increasing the volume of accurate navigation information is offered by the Navstar Global Position Satellite (GPS), which will provide position and velocity information over the entire Earth and at all altitudes.

As a counterpart of the FAA ground-system development effort, NASA is developing the advanced airborne system technology required to safely and efficiently operate aircraft in the future ATC system. These studies, involving applied human factors, include research in the areas of energy management procedures and displays, CDTI, and data-link applications for increased operating efficiency. Not only has a discrete, digital data link been looked at for pilot/ATC controller communication, but automatic aircraft vectoring via data link also is being explored. Potential benefits are reduced pilot technical error, reduced ATC controller work load, and a ground-based area navigation capability.

NASA has conducted time-based metering experiments in the Denver area where the FAA has developed and implemented a local flow management profile descent concept for arrivals into the terminal area. This provides fuel savings by matching aircraft arrival flow to airport acceptance rate. Time control computations allow the pilot to descend at his discretion from cruise altitude to the metering fix and an idle-thrust configuration. NASA Ames developed and flight tested an airborne descent algorithm de-

signed to improve the accuracy of delivering an airplane to a metering fix at a time designated by ATC. The Denver experiments demonstrated that arrival accuracy was improved from the current levels of 1 to 2 minutes using guidance from the radar controllers to more than 10 seconds with the airborne 4-dimensional system. Work load for both the pilots and controllers was also much less with the airborne algorithm.

The potential benefits and liabilities associated with displaying traffic information in the cockpit are being examined in a joint FAA/NASA program utilizing highly integrated simulators and aircraft in flight. The central issue involves the question of proper relationship, or "distributive management" role, of the flight crew to the ATC controller when the crew is presented with a limited display of proximate traffic. Studies to date have defined information requirements and formats for a workable display, and considerable insight has been provided on pilot ability to use the display in flight, such as self-spacing on another aircraft. Yet to be determined are procedures, both operational and regulatory, for using the traffic display. Simulation experiments using CDTI have also been investigated for wake vortex avoidance (see chapter 7).

Aerial Spraying

Though often viewed as glamorous "crop dusting," aerial application operations serve a major economic need in this country. A fleet of approximately 8500 agricultural aircraft accounts for an estimated 10 percent of all U.S. agricultural production through the aerial application of fertilizers, seeds, and pesticides. Faced with serious economic and environmental pressures for improvements in aircraft and dispersal systems, the aerial applications industry asked NASA for help in solving those problems.

By 1977 a comprehensive, long-range aerial applications research plan was started by NASA to improve environmental safety, fuel efficiency, and aircraft productivity and safety. The NASA research effort centered around the following areas.

Drift of chemicals away from their target areas was the major industry concern, both in the U.S. and in other countries, representing not only pollution but direct economic loss. Spray behavior, wake aerodynamics, economic, weather, and biological factors are all in need of improved understanding to solve the problem.

Improved fuel efficiency, productivity, and safety are sought for the aircraft involved in this demanding line of commercial flying. Agricultural aircraft must operate at high angles of attack with good stability, control, and handling. There is virtually no margin for error when flying so close to the ground. These planes spend as much as 30 percent of total mission time in turns, where airspeeds are within a few miles per hour of stall speed. Good turning performance depends on low drag and a high safety level depends on reduced tendency for the wing to drop or roll off at the stall. Wing droop leading-edge modifications from the NASA stall/spin program (see chapter 7) have been recommended as simple retrofits to current agricultural aircraft since stall/spin/spiral/mush accidents account for half of all deaths.

Flight tests with a Thrush agricultural aircraft were made using electronic swath guidance, resulting in ± 1 meter accuracy for row crop spraying. A conventional course deviation indicator (CDI) used for navigation provided the pilot with steering information. The key to practical implementation requires the development of low-cost, highly reliable methods of getting the steering information to the pilot.

Research on dispersal systems has been conducted in wind tunnels and in flight tests seeking to improve pattern uniformity and width. Industry has been highly interested in expanding the performance envelopes of dry material spreaders, sparked by the excess power currently available in the larger, turbine-powered and high-horsepower piston agricultural aircraft. This excess power has the possibility of spreading fertilizer at rates as high as 400 pounds per acre on swath widths as high as 80 feet and at speeds as high as 120 miles per hour.

TOP (Right) Modifications investigated for the Thrush included leading-edge slats for high-lift improvement, ring cowl and wing-to-fuselage fairings for drag reduction, and improved wake characteristics. Also evaluated were wake modification concepts such as vortex attenuating splines and winglets, shown to have beneficial effects on wake-dispersal interaction.

BOTTOM (Right) After tunnel tests, the Thrush was modified to improve application efficiency. Winglets proved able to control the vortices swirling off the wing tips. Moderation of the vortices improved the spray pattern and reduced drift. This was the end product of a long program that began with scale model tests in NASA Langley's wake vortex research facility.

New calibration techniques, such as laser Doppler velocimetry, laser fluorosensing, biodetection, and others offer potential for improved documentation of drift and deposition of chemicals. NASA has evaluated alternative spray accountancy techniques and documented their value for use by industry.

These areas of research involved a number of facilities and tests. At the Langley Vortex Research Facility, small-scale models of agricultural aircraft were used to study aircraft interaction between airplane wake and dispersed materials. An Ayres Thrush S2 R-800 aircraft was mounted in the Langley full-scale 30 x 60-foot wind tunnel to determine its performance; then changes were made to study the effects of drag reduction devices, leading-edge high-lift devices, a turbine engine modification, and wake modification devices. Droplet size distributions were measured by laser spectrometer.

Flight testing at NASA Wallops Flight Center then provided a real-world environment in which the Thrush could validate previous tests. The aircraft was flown with modifications relating to handling qualities, wake vortex modification, and spray distribution. Flying the Thrush for spray measurements proved to be one of the more challenging aspects of the program. For the majority of the tests, the airplane was flown within a foot of the collection tray to get accurate placement of the droplets and the tests were performed between the hours of midnight and 4:00 a.m., when air is the calmest. A series of approach and guidance lights was used to keep the pilot on target—it looked like something out of a science fiction movie.

Near-term results have been realized in drift reduction, stall departure safety, and dry materials dispersal improvements. As a result of this intensive program, computer codes are now available defining wake and spray pattern interaction. The overall agricultural applications data base available can make a great deal of difference to the economic survival of an important U.S. industry.

CHAPTER 7

SAFETY IMPROVEMENTS

The quest for ever safer aircraft has been an overriding concern since the very beginnings of flight. From the formation of NACA, safety research has attempted to match the incredible growth of aviation over the past 80 years, but it has often lagged behind. With NASA's recent emphasis on general aviation, safety has been singled out for intensive study and improvement in stall/spin prevention and recovery, crashworthiness, controls, wake vortex avoidance, and flight in icing conditions.

Stall/Spin

From man's earliest attempts at flight, stall/spin accidents have plagued the development of virtually all types of aircraft. Even today, stall/spin accidents involving general aviation aircraft account for more fatal and serious injuries than any other kind of accident. During the past decade, more than 100 000 Americans were involved in more than 39 000 light plane accidents, and nearly one in four of those accidents are believed to have been due to loss of control after the planes were either purposely or accidentally maneuvered into a stall or spin. Stalling is the sudden loss of lift that results when a wing exceeds its normal operating range. Visualize air flowing smoothly over a wing in level flight. If the angle of the wing is increased more and more, the air begins to deviate from smooth flow. The airstream breaks into turbulent eddies, and the wing—gently or abruptly—loses its lift. Spinning gets its name from the rotational pattern of an airplane in a spin. A

spin may often follow a stall—the nose drops, and the aircraft begins to rotate and lose altitude.

Stall/spin accidents are insidious, usually catching the pilot completely unaware. For example, after experiencing an engine failure on takeoff, the pilot attempts to turn back to the runway quickly before he or she runs out of altitude. Most pilots do not realize that much higher speed is needed to make a rapid 180-degree turn and avoid flow breakaway on the wing. Altitude loss during this turn can be anywhere from 125 to 1000 feet depending on the type of aircraft, and most pilots have no idea how much they will lose in a 180-degree turn for the aircraft they are flying.

Another classic stall/spin accident can occur when turning onto the final approach leg to an airport in a crosswind. The pilot perceives that for the normal bank angle, the turn rate is such that the aircraft will not be lined up with the runway; thus, the pilot banks more steeply and pulls back on the wheel. Suddenly the low wing drops sharply, giving the pilot a shocking closeup view of the ground from a steep banked nosedown attitude. The pilot instinctively pulls back harder on the elevator control and the aircraft enters a deeper secondary stall from which there is insufficient altitude to recover.

Different airplanes have different stall and spin characteristics; one may be forgiving of ham-handedness, while another may seem to have a mind of its own, bent on destruction. Just about the time one general type of airplane is analyzed, tested, and understood, another comes along and presents a new set of problems.

NASA stall/spin research programs go back more than a half century. In 1930, NACA began operating its spin tunnel, a vertical, controlled airstream in which a small, dynamically similar model of a test airplane could be spun in free flight. Clockwork mechanisms activate the model's control surfaces for programmed recovery maneuvers. From that beginning, work grew to include similar tests using a restraining rotary-spin balance to measure the forces in the spin. Today work proceeds in this tunnel, one of only two in the free world.

Other test approaches to stall-spin phenomena have involved standard wind tunnel model tests, radio-controlled flying models,

Stall/spin research airplanes

simulation, and the actual aircraft tested in the full-scale wind tunnel and in free flight. However, most of the research on spin testing through the early 1970's involved military aircraft. When aircraft speeds increased and swept wings entered the picture, general aviation research was left alone until 1973, when the NASA stall/spin program was expanded. The high GA accident rate demanded some specialized research but at first the program was small. The initial goal was to see if World War II research was applicable to current aircraft.

The only data available dealt with tail surface geometry, considered to be the governing factor in spin recovery. However, after a long and extensive series of detailed and rigorous tests, NASA reached the conclusion that tail geometry was not the complete answer to the total spin problem. The wing was a driving mechanism in the stall departure and the tendency to enter a spin for typical GA aircraft, along with a number of other complex factors.

NASA's spin tunnel is the only one of its kind in the free world. Scale weighted and balanced models can be thrown into the tunnel and spun in numerous configurations. Data on spin characteristics as well as spin recovery can be gathered before a full-scale test is conducted. The tunnel has been a vital government resource since long before World War II.

In 1973 a series of flight test programs was initiated with the prototype Grumman American Yankee light single-engine trainer. Different tails were fitted to test their results in spins and these flights revealed the complexity of the spin, which was basically the same with each of the tail units. By 1976, with full funding, a developed spin and recovery program was under way, defining aerodynamics, emergency spin recovery systems (including tail parachutes), and automatic spin prevention systems.

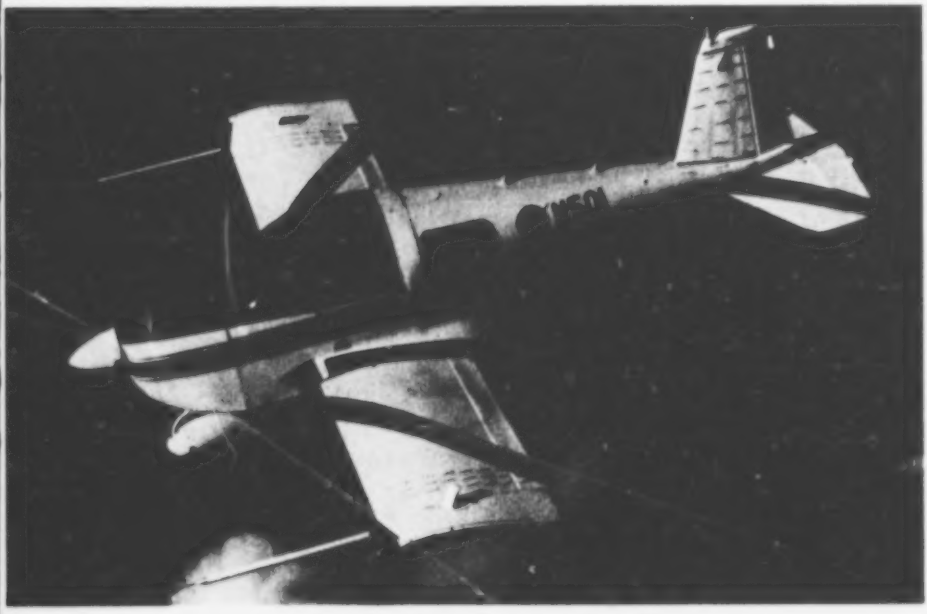
Radio-controlled scale models of GA aircraft proved to be invaluable tools in the program, particularly since they can enter flight regimes that are dangerous in piloted aircraft and then demonstrate recovery procedures without risking lives. One of the more successful early programs was the joint NASA/Beech YT-34C scale spin tunnel and radio control model spin simulation tests that validated use of radio-controlled models in spin testing for GA aircraft.

Since many unswept wings have a tendency to stall asymmetrically (one wing first), thus creating a tendency to spin, wing leading-edge stall strips have been installed on many aircraft. The stall strip locations have often by cut-and-try methods resulted in almost as many variations as there are aircraft. The lack of design information regarding controlled-stall wing characteristics led NASA to study the effects of wing leading-edge modifications on stall/spin characteristics.

Development of differing drooped leading-edge wing extensions on test aircraft proved the point about the powerful effects of wing flow generating separation on spins. With some full-span extensions, even a relatively docile spinner could be made to spin flat, fast, and viciously. But partial-span leading-edge extensions successively made three test airplanes considerably more spin-resistant and more easily recoverable.

Other design characteristics such as high-wing versus low-wing, propeller slipstream, aft fuselage cross-sectional shape, and, still

The initial spin tests with the Yankee were centered around the effects of tail design on spins. Several different tails were built and tested on both the model and full-scale aircraft. The spin recovery parachute can be seen beneath the tail; it was used only for unrecoverable spins.



After extensive testing, NASA researchers found that spins were primarily wing generated, and that the tail configuration played a minor role in comparison. The major breakthrough came with leading-edge wing additions which not only prevented stalls from becoming violent, but also actually made the airplane almost unspinnable. These additions can be seen in red on the outer leading edge of each wing. Note the spin recovery mission markings under the cockpit.

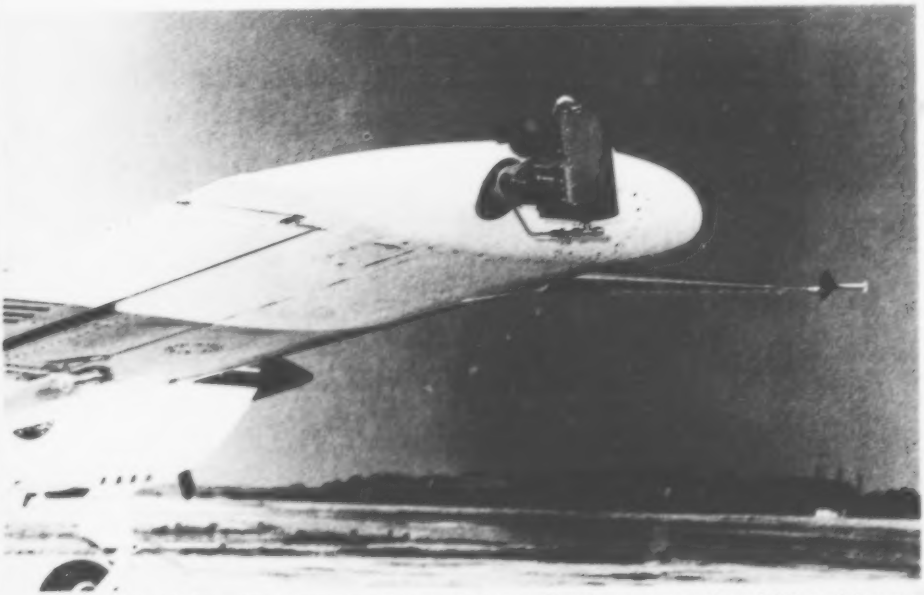
not out of the picture, tail geometry, were found to have certain effects on stall/spin. In some, but certainly not all, a high wing or a T-tail can reduce spin tendencies more effectively.

During flight tests on GA aircraft, a unique control augmentation system of compact hydrogen peroxide thrusters located at the wing tips was installed. Controlled by the pilot, these tiny rockets could be used to help recover from a spin, but they could also be fired in a pro-spin direction during a steady spin to generate much higher spin rates. As a result, the potential existence of flatter, more dangerous spin modes could be investigated and defined.

Another major area of research that has been generally limited to military aircraft is that of limiting pitch control power, now singled out for GA research. Such limitation can make it impossible to stall an airplane by automatically reducing the elevator travel commanded by the pilot's inputs. Mississippi State and Texas A&M universities have flown aircraft with pitch sensors elec-

tronically hooked into the control system so that pitch and throttle are automatically activated or spoilers are deflected under the horizontal tail to prevent a stall. Whether or not these systems will ever find their way into future GA aircraft will depend on the key issues of cost, reliability, maintenance, and system failure characteristics. However, with the increasing sophistication of GA aircraft, particularly light twins, and advances in microprocessors, stall proofing, including flight control following engine failure for twins, is on the horizon.

The spin characteristics of twin-engine aircraft have been investigated in a joint NASA/Beech program involving the new generation light-twin Model 76 Duchess. This is an important step in looking at stall/spin in more complex aircraft. The program included spin tunnel and rotary balance testing with radio control model testing and flight testing, culminating in 150 spin manuevers. Using all the tools now standard for this kind of testing, the Model 76 (not approved for spins) was shown to be



One of the more interesting things about the Sundowner was the addition of thruster rockets to the wing tips, which were used to speed up spins and make them deeper. They also could be used for recovery.

very docile in spins, even with one engine out. This has not only demonstrated that there has been progress in stall/spin technology, it also has demonstrated that there is a great deal more to understand before the aircraft designer has the tools at hand needed for confident design in the stall/spin arena.

The most important lesson to be learned is that stall/spin problems revolve around continual dependence on all facets of technology rather than one area. The introduction of novel configurations such as swept wings, wing-fuselage strakes, long pointed forebodies, T-tails, and many others requires extensive, time-consuming research and development. Unfortunately, the impact of future airplane design tends to be dismissed if the current stall/spin situation is under control. Repeatedly, the designer of a novel configuration finds a complete lack of data base for his or her use.

Advanced canard-type (forward horizontal tail and rear-

A radio-controlled model almost ready to be started for a stall/spin test flight is shown here.

mounted wing) GA designs appear to offer considerable promise for improved performance and inherent stall/spin resistance, particularly Burt Rutan's designs which have amassed an impressive stall/spin safety record. NASA approached Rutan with the possibility of doing extensive tests on his VariEze. After flying a scale model in the spin tunnel, it was found that properly loaded the plane is virtually impossible to spin. However, the problem of wing rock at low speeds with the nose high still remained after testing in the 30 × 60-foot wind tunnel. Installation of the partial span leading-edge drooped modification mentioned earlier completely solved the problem and it was recommended as a change to all VariEze owners. As a result of this testing, NASA hopes to overcome some of the problems with lack of data for designers of advanced configurations. Rutan has considered an advanced canard for the commuter market.

Historically, good stall/spin avoidance has chronically remained

Several wing configurations were tested on the model Yankee, including large winglets.

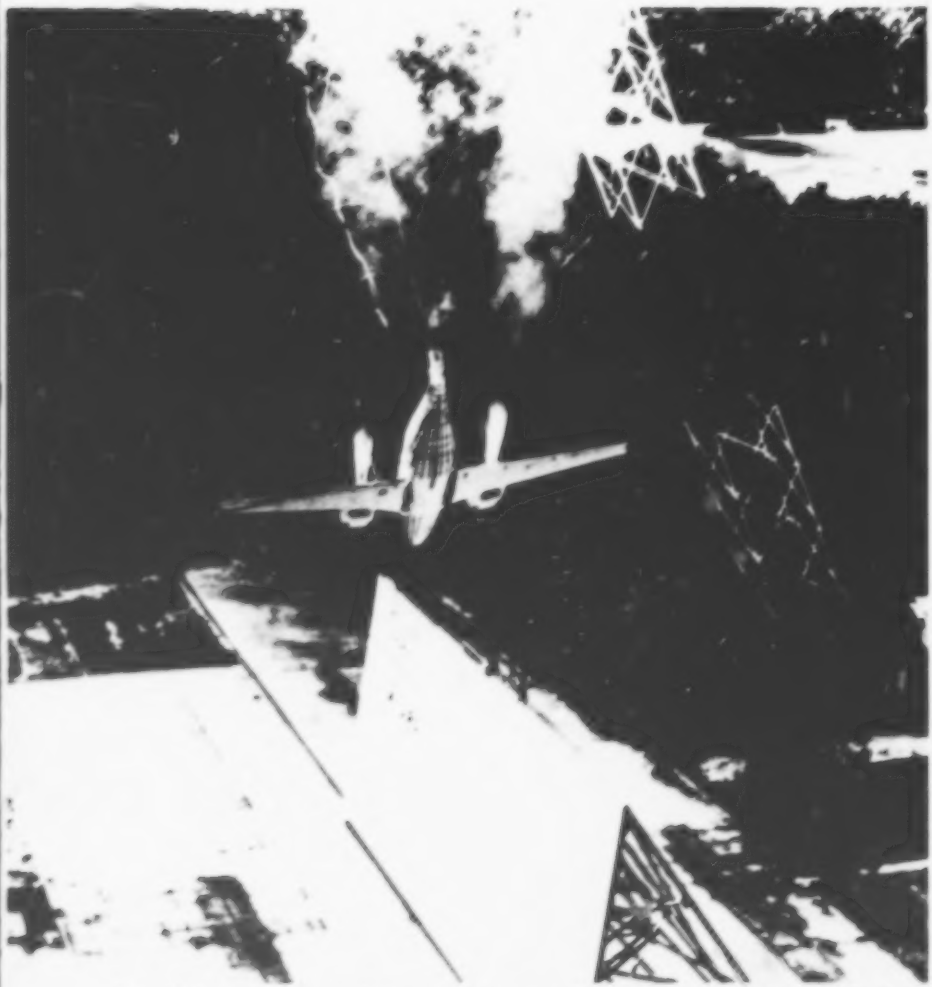
an elusive goal for designers of general aviation aircraft. During the past decade, the technology has rapidly accelerated to the point where improved design methods are available for significantly improved configurations. Rapid design methods and "stall proofing" remain paramount, hinging on control of stall progression of the wing, development of an acceptable means to limit pitch control, and minimization of adverse cross-coupling effects by automatic means. Slowly the research emphasis has progressed from stall/spin recovery to prevention, and the future for safe general aviation flying has never looked brighter.

Crashworthiness

In 1972, NASA and the FAA embarked on a cooperative effort to develop technology for improved crashworthiness and passenger survivability in general aviation aircraft with little or no increase in weight and acceptable cost. Since then, NASA has "crashed" dozens of GA aircraft by using the lunar excursion module (LEM) facility originally built for the Apollo program.

The LEM test rig at Langley was converted to drop airframes onto a typical runway surface in a carefully controlled, extensively instrumented environment. Photographic and other data are recorded during the few milliseconds of the shattering impact. Anthropomorphic dummies harnessed in crew and passenger seats contain additional instrumentation to assess the loads imposed during a crash. Normal impact speeds of about 60 miles per hour are reached but a few tests have been made at speeds up to 100 miles per hour by using Falcon missile rocket motors.

The aircraft is suspended from the top of the gantry by two swing cables and is drawn back above the impact surface by a cable. The plane is then released from the pullback cable, permitting it to swing like a pendulum into the ground. The swing cables are separated from the aircraft by explosive charges just prior to impact, thus approximating actual flight. The data umbilical remains attached as the crash takes place, but it is also separated by an explosive charge before becoming taut during skid out. Flight path angle is adjusted from 0° to 60° by changing the length of the swing cable. The height of the aircraft above the ground at release determines the impact velocity.



Four Falcon air-to-air rocket engines were used to accelerate this Navajo to 145 km per hour with a pitch angle of − 30 degrees. For greater survival probability in an aircraft crash, the fuselage should remain intact. Researchers also investigated seat integrity and restraint systems, as well as seat design.

These tests emphasize development of the capability to predict the dynamic response of an airplane's structure during the impact. How will it deflect and how will it break? How does it absorb energy or transfer the shock of impact to seats and occupants? If these questions can be answered analytically, it will greatly reduce the design difficulties in future aircraft development programs.

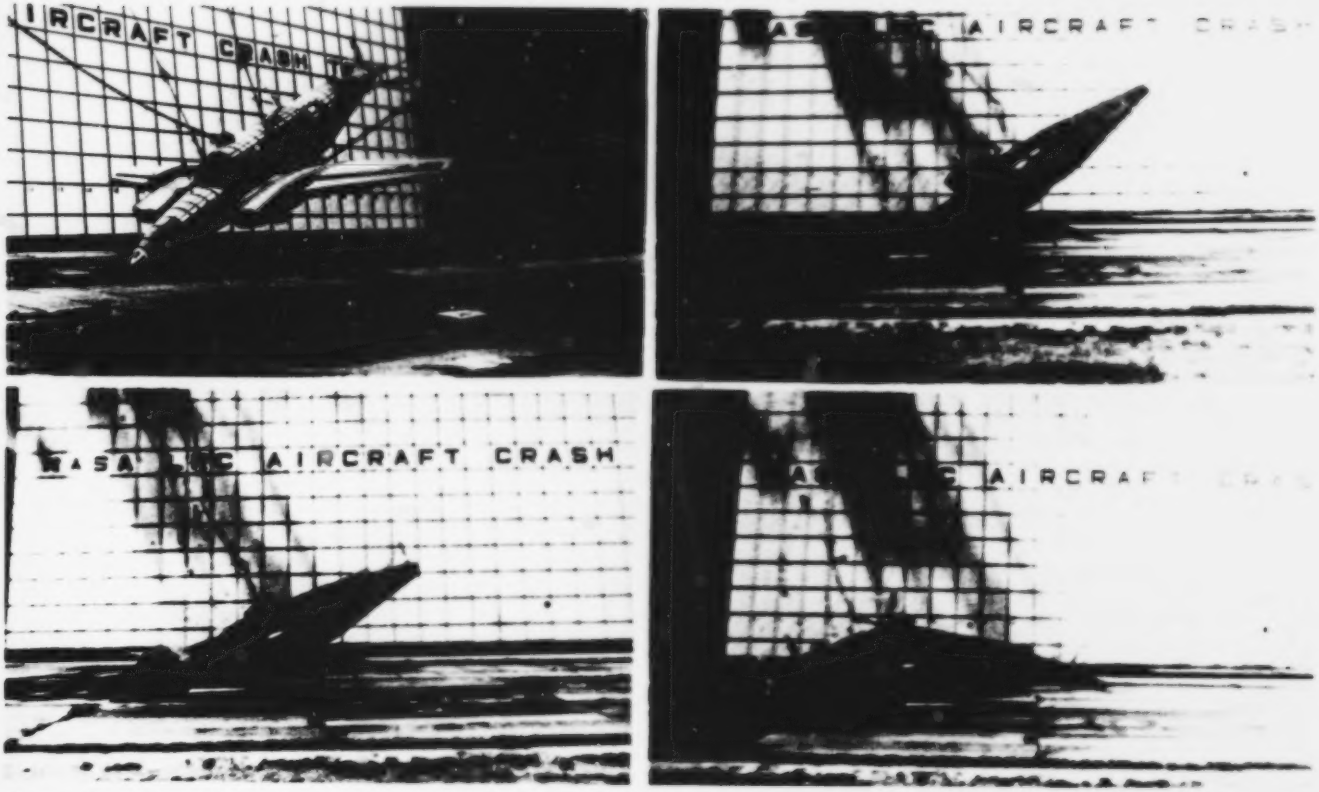
This Navajo is impacting the concrete at 60 mph.

Current structural analyses do not apply to the special conditions of aircraft crashes, and NASA is endeavoring to extend them so that they will.

Involved in these tests are seat, safety harness, and floor designs. A data base was developed so that the FAA could adequately define its dynamic seat testing. A computer program for modeling the crash behavior of seats and subfloor structures is now available to industry.

An important focal point of the program is testing of crushable aircraft subfloor sections. These are designed to crumple progressively at impact to absorb some of the energy of the crash and reduce the forces that the passengers feel. In some of the NASA tests, the floor and the seats attached were undamaged, even though the subfloor was crushed.

The key to this very dramatic testing is the ability to watch an aircraft in slow motion with extensive data input about what is actually happening. It is one thing to look at an aircraft accident in



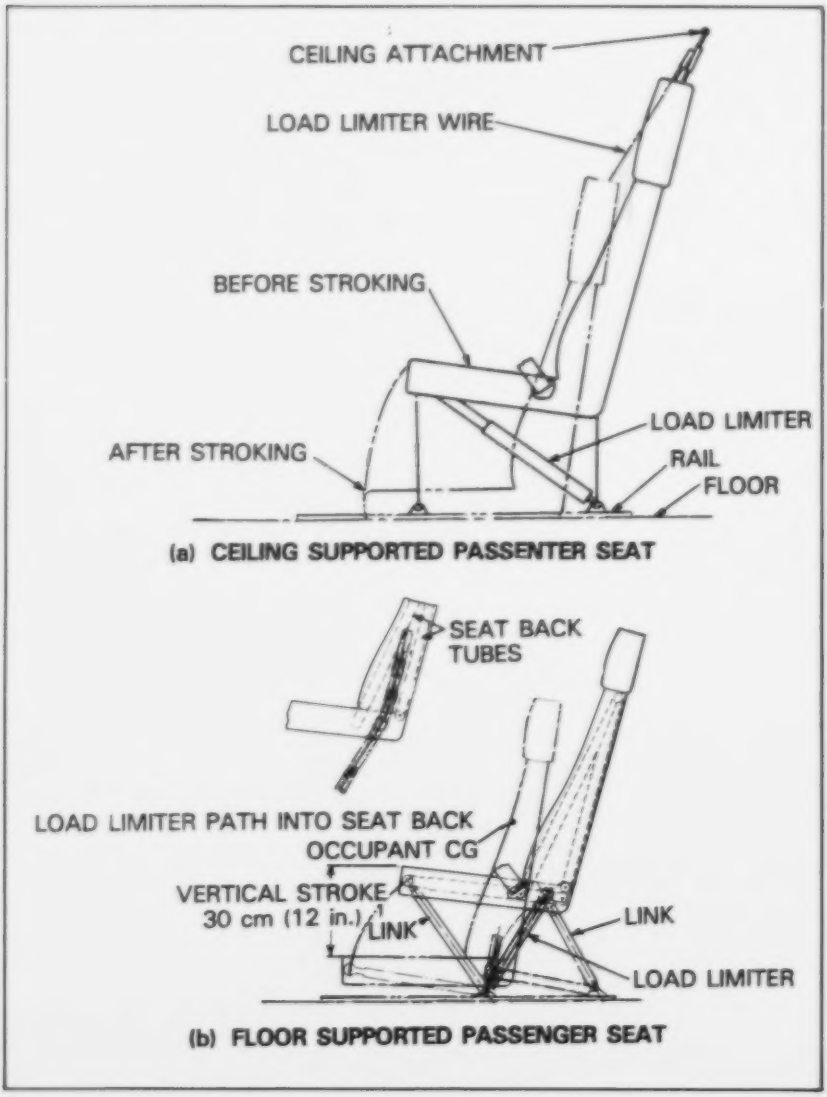
Shown here is a crash sequence as a Navajo hits the concrete at 145 km per second.

reverse, so to speak, through investigation; but this does not provide the opportunity to follow it through without guesswork. Even the best crash investigators come up with different results, and each sees something different when examining a NASA crash test.

NASA has discovered that little research has been done on cabin volume destruction. At least two-thirds of aircraft crashes resulting in death have left cabin volume essentially intact. What this says is that linear (forward) acceleration is not the real killer, but the load as the aircraft impacts vertically. The bottom floor of the fuselage absorbs all of the load—there is twice as much load vertically than horizontally. Yet, the human body is twice as vulnerable to G-forces (force of gravity multiplied) vertically than horizontally. Normal human G tolerances are 45 Gs horizontally, 25 Gs vertically, and 20 Gs laterally. In other words, the spine is crushed. There is such a thing as a floor that is too strong (stiff). This has been a major breakthrough in the program, pointing toward true crashworthiness.

In addition, the crush zone under the fuselage of a light twin distorts upwards and to the side, forming a bow. This throws passengers violently into the sides of the aircraft. A new concept is a 2-inch-thick, reinforced floor plate with tuned structures underneath to absorb 20 to 25 Gs, dissipating the force of the crash before the spine is crushed. A 12- to 18-G tolerant seat is in the offing but a strong seat pan is needed as reinforcement for the torso; the area beneath the seat itself has to be tuned as well. Harnesses and lap belts need to be placed where there is some natural human strength—across the hip bones with the harness at 0° to the back so that the passenger does not slide out from under it. One of the prime customers for crashworthy seats has been Wycliffe Bible Translators' mission flying arm, the Jungle Aviation and Radio Service (JAARS). Crashes on the far-flung mission fields have taken many lives in some of the most demanding flying conditions. JAARS and NASA have been working together and have retrofitted several mission aircraft with better seats.

Several of these load-limiting seats have been tested in Langley's hydraulic loader, where ever-increasing loads can be put on any structure until it fails and then researchers can watch what happens at that point. Several seats can take the loads, but when they fail they end up trapping the occupant's legs underneath.



Floor supported and ceiling supported passenger seats have been the subject of much research in the NASA crashworthiness program. Since humans can endure horizontal deceleration much better than vertical impact, seats have been redesigned accordingly. Crashworthy seats designed at NASA are currently flying in Jungle Aviation and Radio Service aircraft serving missionaries around the world.

With every solution there are new problems to solve since so little has been done previously in the area.

Controls and Human Factors

Though this sounds rather basic, controls are the heart of connecting the pilot's (or autopilot's) wishes to the airframe and power plant. NASA has conducted ongoing research into how human beings interact with aircraft controls. With the ever-increasing complexity of general aviation aircraft, particularly in the capability of their systems, pilots are in need of simple controls that require no diversion of effort. Not only does the pilot have to fly, he or she must also navigate, monitor the cockpit displays, monitor the engines, and select the safest manner in which to perform the mission, particularly in instrument flight rule (IFR) conditions (see chapter 8).

NASA's aircraft energy efficiency program (ACEE), centered around large airline transports, has investigated a number of human factors areas that are beneficial to general aviation. All aircraft systems interact, and design must take into account the effect one change will have on other systems.

Modern control technology considers the effect of aeroelasticity to reduce loads with highly flexible structures. Maneuver loads can be controlled on high-aspect-ratio wings to take advantage of improved aerodynamic performance. Gust loads also can be controlled to reduce fatigue damage, improve ride quality, and reduce wing-bending moments. Weight penalties for flutter can be minimized or eliminated with active flutter suppression systems. Successful application of these concepts requires improved methods for unsteady load prediction, integrated design techniques, and improved reliability of components and subsystems.

The heart of this ability to move controls independently of the pilot's input is the computer. Fly-by-wire systems represent leaving the old tube and cable control systems behind. In other words, the pilot or computer is connected to the control surfaces by electronic wiring and not by direct controls. The electronic impulse moves the controls through a system that takes into account mean time between failures.

These active controls are already being flown on large transports such as the Lockheed L-1011, but if they fail the pilot

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can still control the aircraft. Full authority active control and performance benefits from such factors as relaxed static stability remain in the future for GA aircraft, but the potential for great increases in fuel efficiency due to minimizing weight and drag is very promising.

The revolution in digital electronics has dramatically affected the design and capabilities of emerging avionics systems because of the spectacular reduction in cost, size, and power required of digital electronic components. Although digital systems have been used for a number of years in navigation and other onboard applications, they are now emerging in safety-critical flight controls. The new generation of civil transports such as the L-1011-500, DC-9 Super 80, and the Boeing 757/767 family utilize digital flight control systems. In the far term, reliable microprocessors will increase safety and utility and further decrease the cost of avionics systems (see chapter 8).

In addition to the potential improvements in fuel efficiency and reduced operating costs offered by digital fly-by-wire flight control systems, the use of electromechanical actuators in lieu of hydraulic actuators with these systems offers additional benefits. Though they have been under development for aircraft for many years, newer, smaller electric motors have made their use more realistic because of the reduced size, weight, and power requirements compared to older motors. Replacing the hydraulic actuators with electromechanical actuators could allow the removal of the entire hydraulic system (actuators, servos, pumps, line, and valves).

The major deterrent to the widespread use of integrated avionics is systems reliability—a systems probability of failure of less than 10^{-9} at one hour, three orders of magnitude better than the triplex systems of today, must be achieved. In order to reach these levels, two experimental fault-tolerant computer concepts are being developed at Langley. Both concepts use redundant computer elements, but each employs a different approach to fault detection and isolation (software voting versus hardware voting).

An advanced avionic or "all-electric" airplane, such as the military F-16 fighter, requires careful integration of the airplane with the crew via advanced flight decks. Over the past several

years, numerous flight experiments have been conducted using the NASA advanced transport operating systems (ATOPS) aircraft, a Boeing 737-100 equipped with a research cockpit located in the cabin area. From this experimental flight deck, the airplane has been flown using a fly-by-wire control system, electronic displays, and pilot-selectable automatic navigation, guidance, and control functions in simulated Category III (the most demanding IFR) conditions. Results from these tests have gone into the Boeing 757/767, but applications for general aviation aircraft also are being investigated.

The crew's role in the future will continue to move toward one of manager of more automated flight systems. Advanced crew stations will require additional research to assure proper integration, and toward this end NASA and Lockheed-Georgia are developing an advanced concepts simulator design that can be used as a starting point. A number of candidate cockpit layouts were examined looking at both conventional and futuristic configurations. A desk-like console design has been chosen and a mockup has been made to look at initial placement of pilot controls, electronic displays, multifunction/multimode keyboards, touch panels, and voice recognition devices. Certainly the day of advanced human engineering for safer flying is near.

There are many other smaller programs being conducted involving control improvement which have nothing to do with electronics. Improved ailerons, elevators, and rudders directly aid the pilot in controlling the flight path of an airplane.

Landings present a challenging task for general aviation pilots of small aircraft. Not only do many people find landings hard to master, but the approach and landing phase of operation represents a period of high accident risk. Overall, approximately 50 percent of all general aviation accidents involve landings, with the approach phase (overshoots, undershoots, or collision with objects) being the primary cause. Glide path control certainly relates directly to these accidents.

NASA sponsored a study to evaluate the application of upper surface hinged-plate spoilers and lower surface dive brakes similar to those used on sailplanes to the wings of a Beech Musketeer. Four different configurations were determined, and flights were made under a wide range of flight conditions with pilots ranging

from students to advanced commercial pilots. The results were very encouraging for such a simple system.

Spoilers offered significant improvements in the aircraft's performance and flying qualities for all elements of approach and landing. Spoiler deployment was linked to power changes so that the throttle became the flight path controller. Touchdown accuracy and ease were much improved for all the pilots taking part. With the results available to industry, safer GA aircraft can be designed.

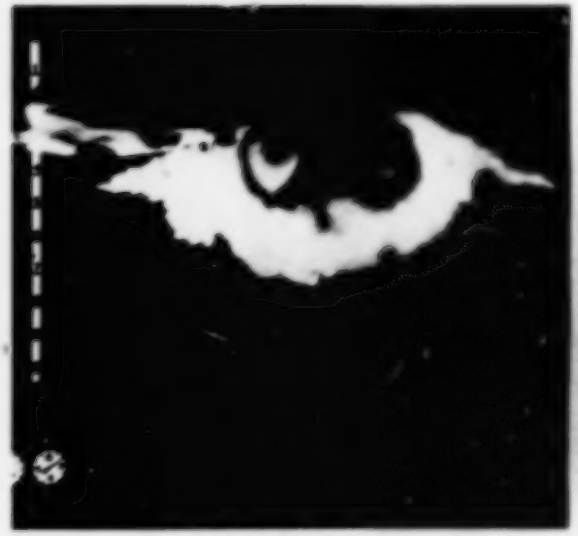
Wake Vortex Hazards

An invisible danger to small aircraft is continually present at large airports. The wakes of heavy transports during landing or takeoff create horizontal whirlwinds that can upset a lighter aircraft flown into their trailing envelope. When this phenomenon was both experienced and identified at least 20 years ago, it became a matter of intense concern to the FAA. It remains unsolved, and is one of the agency's highest safety priorities.

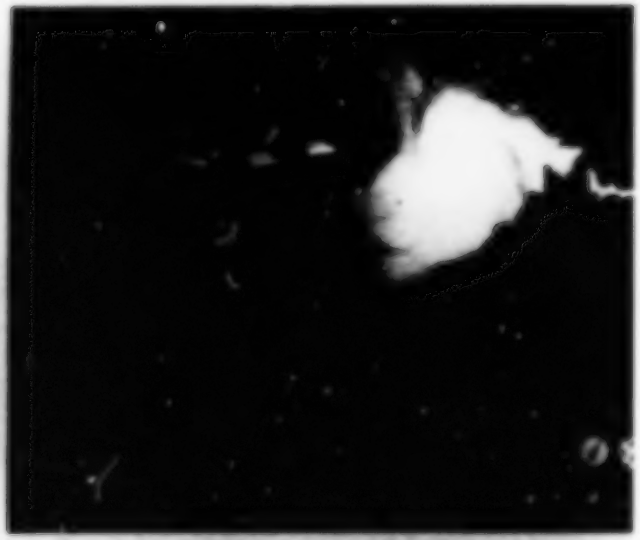
NASA has conducted a variety of flight experiments to try to reduce the strength of the wake vortex and thereby make it less dangerous. None of the methods has proved to be promising, and none has been proved practical by flight verification. This disappointing outlook has prompted NASA to direct its studies toward fundamental wind tunnel and analytical investigations to understand the mechanism of the wake vortex. Following that, it should be possible to both predict the formation and dissipation of vortices and to control them. This work is of great importance to GA aircraft owners and operators.

In addition, current restrictions on aircraft separation distance during approaches to airports are set because of the wake vortex hazard. Under IFR conditions, this restriction extends to six miles or more for a light aircraft behind a large, wide-body transport. Airport congestion, which severely limits the operation of all types of aircraft, will not be relieved until this restriction is removed. NASA's approach to the problem is two-pronged—wake avoidance and wake attenuation.

Under visual flight rules (VFR), flight crews routinely reduce their in-trail separation behind other aircraft. They avoid the wake



NORMAL VORTEX



DISSIPATED VORTEX

Wake vortex dissipation has been the focus of much NASA research, since aircraft caught in vortices virtually lose control. As seen here, these vortices can be made less vicious.

vortex by piloting their aircraft along a slightly altered trajectory. Simulation experiments have been undertaken whereby the lead aircraft is displayed on an advanced cockpit heads-up display that also provides a computer-drawn runway symbol and other guidance information. Consecutive aircraft approaching the same runway will be on different flight paths having a different glide-slope angle and a different runway intercept. The challenge is to provide a display that will permit the crew to maintain a prescribed separation and monitor the operation of the preceding aircraft for deviation from a nominal descent on its prescribed approach path.

Recent research in wake vortex attenuation has shown that altering the span-wise loading (for example, retracting outboard flaps) generates systems of vortices that interact to produce earlier dissipation of the vortex core. The use of spoilers to alter the load distribution as well as to generate turbulence is also effective. NASA Langley's unique vortex research facility has proven invaluable in trying to solve this significant problem.

At a simulated distance of 2.6 nautical miles downstream of the airplane, the vortex pattern was seen to be breaking up. This attenuation also was observed in flight tests with a Boeing 747. One of the more important results of this effort was the discovery that by oscillating the spoilers and ailerons in a maneuver that produced a periodic aircraft roll, essentially total wake alleviation could be achieved. While this was obviously not operationally acceptable both on the part of passenger comfort and consistent flight path, it did demonstrate that attenuation is possible.

Icing and Lightning

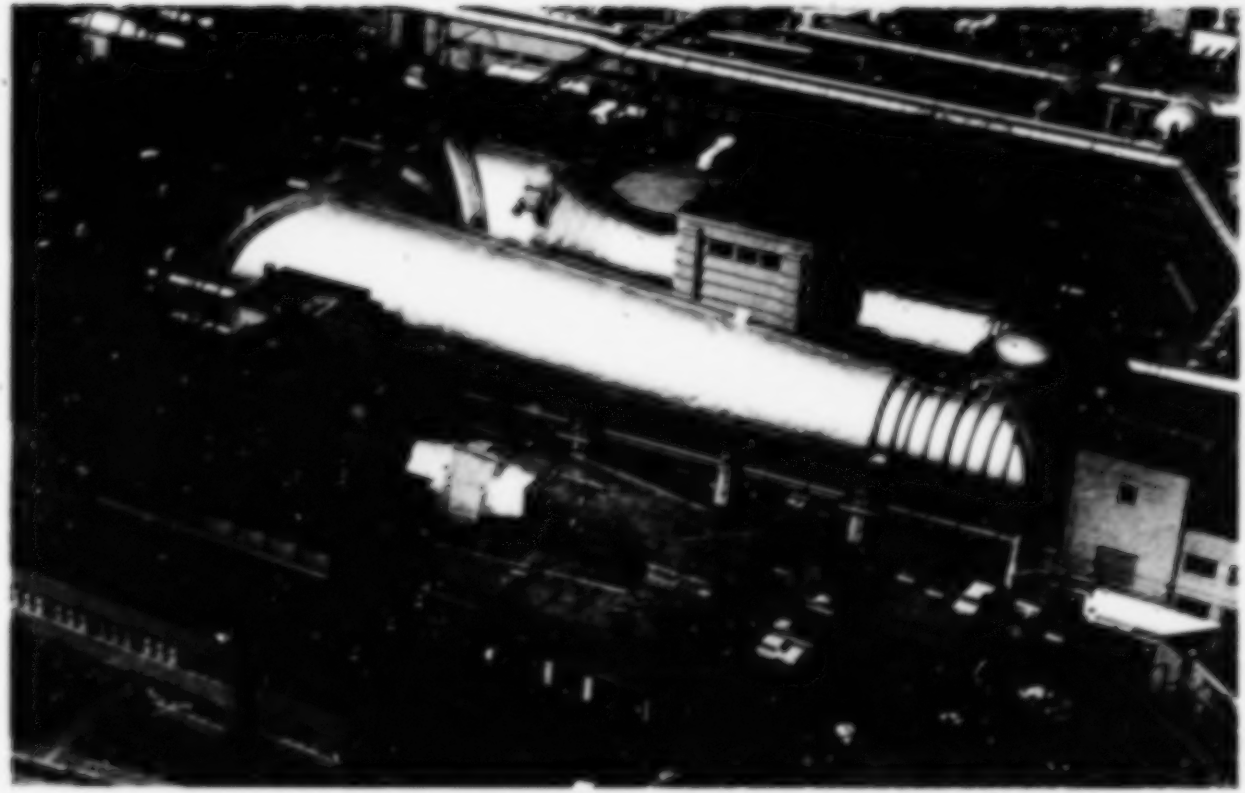
Since man's first powered flights, weather has been a continual source of problems and has remained a major cause of accidents. Improvement in IFR flying technique remains a major NASA concern (see chapter 8), but storm hazards and how to best operate aircraft in the vicinity of severe storms is of vital importance as well. Two areas of particular concern are lightning and icing conditions.

Considerable uncertainty exists about the way composite materials react to direct lightning strikes. Digital electronic control and avionic systems also need to be protected against possi-

Until recently, there has been no in-depth research on lightning strikes and their effects on aircraft in flight. This picture shows NASA flying an F-106B fighter into the heart of thunderstorms. Hundreds of strikes have been recorded, adding invaluable data about what lightning does, where it comes from, and where it goes.

ble catastrophic effects. Almost all engineering data available on lightning characteristics have been obtained from cloud-to-cloud strokes to instrumented towers. Characteristics of lightning at flight altitudes have not been measured before.

NASA is currently obtaining new data by flying a heavily instrumented F-106B aircraft into thunderstorms, getting struck by lightning, and measuring current and the electric and magnetic flux rates of change to 10 nanoseconds time resolution. Lightning strike patterns on the aircraft have been carefully documented. Several swept strokes across the wing mid-span have occurred, an unexpected phenomenon requiring further study. Numerous transients have been measured as a result of these strikes, with peak current recorded at 15 000 amps. In essense, a door has opened.



The NASA Lewis Research Center Icing Research Tunnel is shown here.

revealing an area of research that is virtually untouched. Researchers have come to realize they know almost nothing about lightning. Where it is potentially dangerous and where it is not remains to be discovered and the results will prove vital to all forms of aviation.

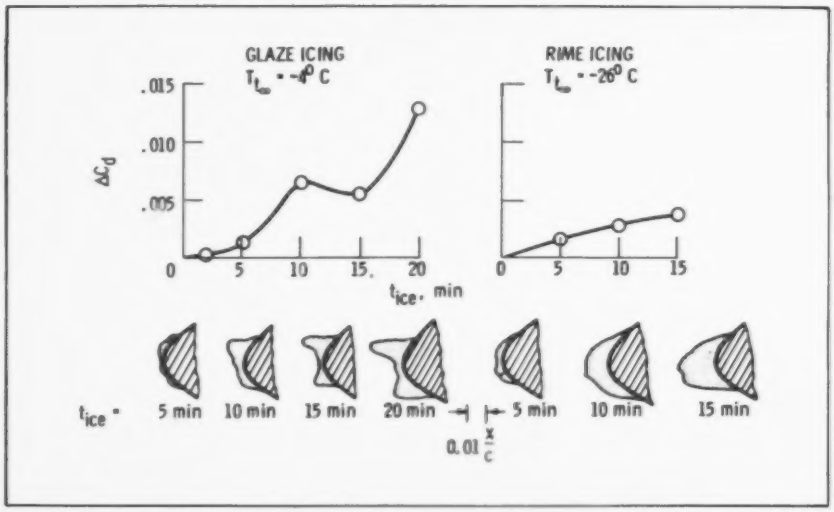
Over the last few years, an increasing need has surfaced for advances in ice protection technology. The increasing cost of fuel has prompted aircraft designers to seek better ice protection systems to save weight and fuel. During the 1940's and 1950's, both NACA and industry helped solve the icing problems for those aircraft that flew IFR, which included mainly commercial and military transports, a few general aviation aircraft, and no helicopters. Today, technological advances in avionics and flight controls make it possible for nearly all helicopters and GA aircraft to be equipped to fly IFR.

Many of today's GA aircraft are certified for flight into icing conditions, but they rely on ice protection technology that is over 20 years old. The relatively small payload fraction and low power margins of these smaller aircraft mean that their ice protection systems must be lightweight and low in power consumption. Since small objects collect ice faster than large objects, all the serious problems of icing happen faster and are more serious on small, unprotected aircraft—drag rise, torque rise, power loss, lift deterioration, stall angle decrease, and stall speed increase.

In response to this need, NASA has reestablished an icing research effort at the Lewis Research Center, centered around the reopened Icing Research Tunnel. The objectives of this research encompass improved icing forecast capability, more accurate ice detection instrumentation, low-cost protection systems, improved testing facilities and techniques, and widespread use of large, high-speed computers to lower development and flight certification costs and methods. These include both short-term goals over the next 5 years and long-term goals extending over 10 years.

Since general aviation aircraft spend such large amounts of time in the low-altitude icing environment, development of improved icing protection systems is very important. Glycol fluid systems, electromagnetic impulse deicers, and icephobics are being investigated.

There is considerable interest in freezing-point depressant



Depicted here is a comparison of glazed and rimed icing in cruise conditions. Glaze icing has proved to form in horned shapes compared with rime icing.

systems. Under a NASA grant, the University of Kansas has tested glycol fluid on two modern GA airfoils in the Icing Research Tunnel. The porous composite or stainless steel distributors are not only efficient, but they also can be used to keep insect debris off laminar flow wings.

Electromagnetic impulse deicers offer a potential alternative to conventional hot-gas anti-icing systems. A capacitor is discharged through a coil of wire and the magnetic field induces eddy currents in the airfoil skin, causing it to deflect rapidly and break the ice off. Though much research remains to be done, the initial results look promising.

Icephobics is the name given to any material that reduces the ability of ice to stick to a surface. Besides reducing the adhesive bond of ice, an icephobic suitable for aircraft must also resist rain and sand erosion, must not be carried away by the shed ice, and must withstand exposure to weather including the Sun's heat and ultraviolet rays. A joint NASA/Air Force/Army program failed to produce a successful icephobic out of several attempts, but a current grant with Clarkson College of Technology is continuing the effort.

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Instrumentation to determine drop size and liquid water content in clouds has been tested in the icing tunnel, finding a direct correlation between droplet size and ice shape and drag on a NACA airfoil. Ice shape changed significantly and the resulting drag coefficient changed by a factor of five. NASA has funded Ideal Research to develop a microwave instrument to detect ice on the surface of an aircraft component and to measure the ice thickness and growth rate. Further development is needed to demonstrate that the instrument can distinguish between water and ice, because under glaze (clear) icing conditions both water and ice are present on the surface.

NASA experimental methods center around the Icing Research Tunnel, the largest icing wind tunnel in North America, with a 6 × 9 × 20-foot long test section capable of 300-mile-per-hour winds and temperatures down to −30° F. Able to operate year-round, the tunnel has 77 air atomizing water nozzles that produce a simulated icing cloud with variable liquid water content from sea level to 3000 feet. The tunnel was built in 1944 and needs to be rebuilt, but it is in continual use with a two-year backlog of test results. Full-scale components such as airfoils and engine inlets, even propellers and engines can be tested in the main section.

There is a universal need for data on aerodynamic degradation to two-dimensional airfoils in icing. The data from the 1940's and 1950's often do not agree with the results for new airfoils tested in the tunnel. One airfoil has a blunt leading edge that gives higher maximum lift coefficients and better stall characteristics than the older airfoils. Icing results were different. Other modern airfoils, such as laminar flow control wings and supercritical wings, will be tested in the tunnel to see how ice affects their aerodynamic performance.

A full-scale general aviation wing with a NACA airfoil section was tested in the icing tunnel to determine what rime (cloudy, air filled) and glaze (clear) ice would do at cruise and climb conditions. Drag increases of about 130 percent were measured for a 20-minute glaze icing encounter in cruise. The drag increased by approximately 40 percent for a 15-minute rime icing encounter in the same conditions. The NACA wing section was found to be less sensitive to rime and glaze ice accumulations in climb (higher angle of attack) conditions. Observed aft frost layer growths con-

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Ice has accumulated on this wing section in the icing tunnel. Tests have shown glaze and rime ice collect in different ways and often in bizzare patterns, which disturb airflow even more than previously anticipated.

tributed significantly to the measured increase in section drag. Comparisons of measured increases in section drag due to primary ice accumulation with predictions of NACA drag correlation indicated agreement was as good as that for the original data on which the correlation was based. Agreement was less satisfactory for the higher liquid water content cases compared.

High-speed computers are now available to model ice accretion and analyze the complex flow around airfoils with rough, irregularly shaped ice caps that can cause flow separation and reattachment. To measure the physics of such an aerodynamic flow model, artificial ice shapes made of wood are being used in the tunnel without the icing cloud turned on. Drag values for both the real ice and wood replica turned out to be very close for both rime and glaze ice. Verified icing scaling laws are also needed to permit accurate tests at actual facility conditions and to permit tests of small-scale aircraft models.

The long-term goal is to use computers to predict the details of an aircraft icing encounter. As computer codes have speeded up so many other processes, such as airfoil design, they will be developed to predict changes in overall aircraft performance and aircraft handling characteristics due to ice buildup on unprotected surfaces. Through 1980 there were virtually no icing analysis codes published and the increasing costs of icing flight tests provide strong motivation to develop the codes.

Lewis has started an icing research flight program using the NASA deHavilland Twin Otter. The twin-engine aircraft has been flown out of Lewis during the icing season from November through April; a major intention is to ensure that researchers conducting icing tests in the tunnel or developing computer codes have firsthand knowledge of how their results compare with flight test results in real icing conditions. During the flights, validation data for icing simulation will be conducted on the same cylinders and airfoils being tested in the tunnel, instrumentation will be evaluated, icing cloud data will be recorded, and ice cloud forecasting will be investigated. NASA and Ohio State University are also conducting inflight icing experiments to measure lift and drag degradation on the Twin Otter's wings, as well as overall airplane performance loss. Flight results are being compared with tests in the tunnel of a Twin Otter wing section.

CHAPTER 8

ELECTRONICS AND AVIONICS

The general aviation pilot is faced with ever-increasing complexity as he or she uses the modern airspace system. It is becoming more difficult to fly between major cities without the help of electronic wizardry in different forms. NASA has been involved in many research efforts geared toward helping the GA pilot cope with the demands of modern flying with improved safety and efficiency.

Single Pilot Instrument Flying

In 1978 NASA Langley began investigating the problems of single-pilot IFR (instrument flight rule) flying, or SPIFR for short. Reflecting the trend of GA dominating U.S. airspace, IFR flying in 1981 involved 10.2 million airline, 4.6 million air taxi and commuter, 3.9 million military, and 18.5 million general aviation operations. By 1993 GA IFR operations alone are forecast to increase to 30.4 million.

A large portion, in some cases most, of the IFR operations in three of the categories (commuter, GA, military) involve a single crewman who is expected to perform as effectively as the two- or three-person crew of airline transport class aircraft. It is generally thought by many that this level of effectiveness does not exist since a large number of SPIFR operations involve relatively inexperienced pilots, often having limited equipment.

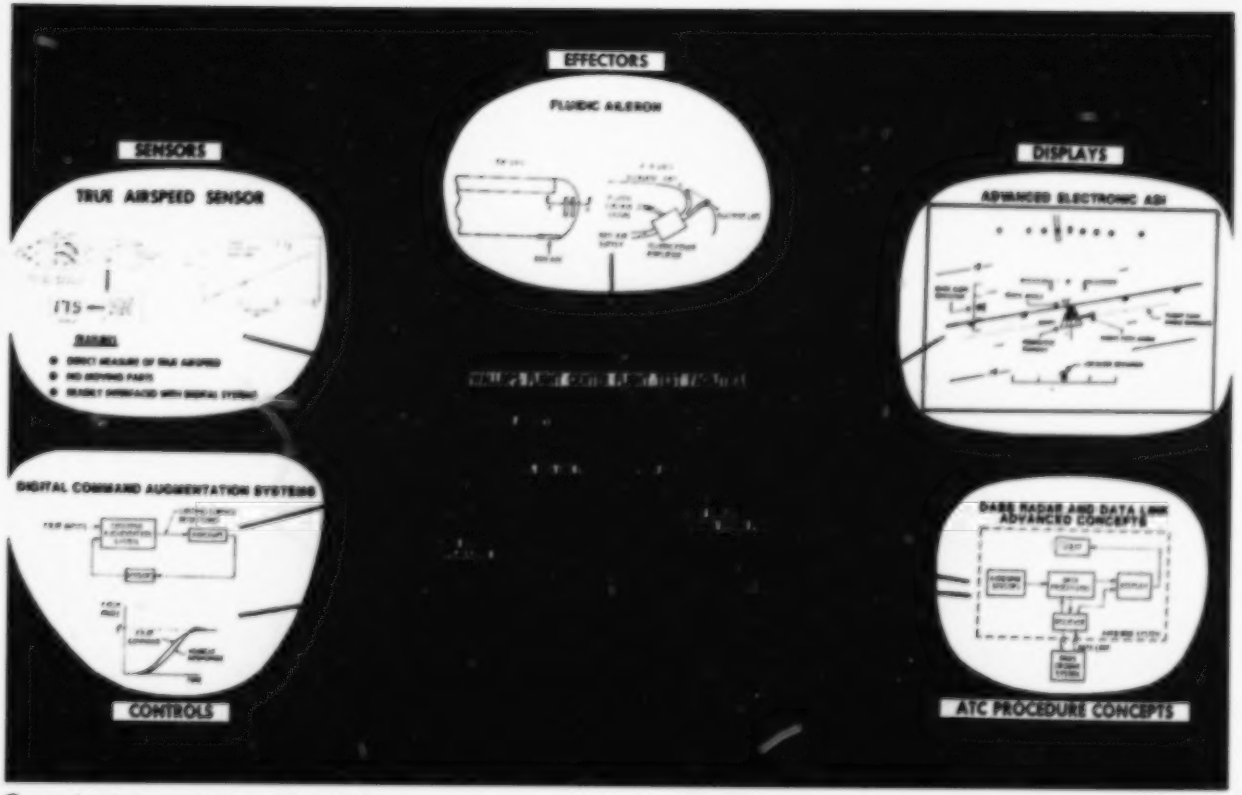
Although the GA accident rate has improved as a whole, a recent analysis for GA SPIFR shows that single-pilot operations ac-

count for 79 percent of all accidents during IFR operations. About 50 percent of the single-engine accidents occur in the high work load landing phase of flight, and there are 10 times as many accidents at night. The findings also indicated that about half of the accidents are controlled collisions with the ground, a situation where the airplane is functioning normally and the pilot flies into the terrain because of lack of situational awareness. SPIFR accidents based on pilot error are predicted to increase from about 150 a year to 250 a year by 1993.

Under NASA's SPIFR program a nationwide survey of 5000 currently rated IFR pilots was conducted to identify problem areas and possible solution concepts. Typical problems included timely weather information and dissemination, air traffic control (ATC) inflight demands and high cockpit work load, complex or excessive ATC procedures, navigation chart format or content, interior noise, inadequate cockpit lighting, and maintaining recency of experience. These pilots listed their most common errors: not planning ahead, overconfidence in their ability to cope with weather, exceeding their personal capabilities, misunderstanding ATC transmissions, and descending below minimum descent altitudes. Specific solution concepts included better and more accurate weather information in the cockpit, better pilot interface with increased automation and display formats, and data link for enhanced information transfer.

An investigation into pilot interface with aircraft automation was undertaken. An autopilot complexity/benefit tradeoff study evaluated the relative benefit of various levels of state-of-the-art autopilot complexity. As it turned out, the more complex the autopilot, the more frequent the pilot blunders. The least errors occurred when only a wing leveler and heading-select system were used. Researchers believe that many pilots lose awareness of their aircraft's situation when they become "autopilot managers." Often these pilots worry about subtle system failures instead of flying the aircraft. Poor pilot interface with automation was thought to be the reason, a disturbing result since the pilots surveyed preferred more automation to help in their IFR flying.

Although it appears automation can reduce work load, too much automation requires too much pilot monitoring. There is a great need for more research into human factors, pilot training,



General aviation avionics and control

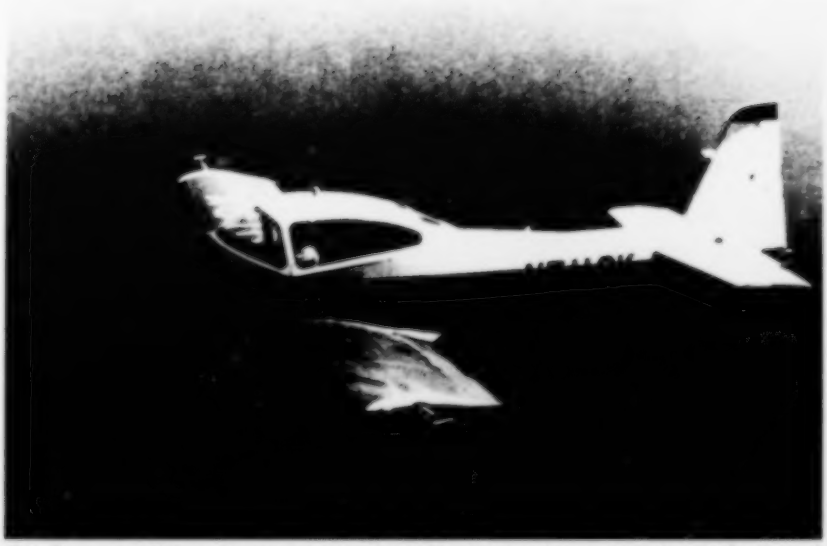
and pilot interface with new technology. A second study used the same simulator and flight scenario to evaluate an automatic terminal approach system (ATAS) concept, which automatically flew instrument approaches by using stored instrument approach data to control the simulator's autopilot and tune the radios. The ATAS also can execute a missed approach unless the pilot takes over to land. This represents a level of automation well above the highest level evaluated during the first study. The results were encouraging; there was lower pilot work load and fewer pilot blunders were committed with ATAS than with a low-level autopilot mode that in the first study had relatively few pilot blunders. The reason for the improvement was a much better pilot interface with ATAS that enabled the pilot to maintain situational awareness during the automatic approaches.

Automated Pilot Advisory System

One of the more interesting systems tested to help the pilot cope with entering an airport traffic area was the automated pilot advisory system (APAS). Its basic components are a primary radar system, tracking computer, weather sensors, a minicomputer, and a VHF radio transmitter. Data from the tracking computer and the weather sensors (wind, pressure, temperature, dew point) are fed into the minicomputer, which then organizes the data and selects from a memory of 64 prerecorded words and phrases to transmit the information to pilots. The minicomputer also analyzes data from the wind sensor to advise pilots of the best landing runway from as many as six.

Using the automated voice system, APAS transmits an airport advisory every two minutes, consisting of airport identification, Greenwich mean time, wind direction and speed, favored or active runway, altimeter setting, temperature, and dew point. At 20-second intervals, between the airport advisories, APAS transmits traffic advisories, calling traffic in the pattern first, then arriving and departing aircraft, and finally aircraft flying overhead above pattern altitude. While APAS can track up to 20 aircraft at a time, it issues advisories on a maximum of 10.

The APAS test facility was located at Manassas Airport, Virginia. The primary goal of the system is to meet the future growth of general aviation in the next decade, placing greater traf-



The Princeton University avionics research Navion has been at the heart of much of NASA single pilot IFR research. Many systems have been installed and tested in this aircraft for actual hands-on experience in the instrument flying environment.

fic demands on the uncontrolled (no control tower) airports. The FAA estimates that a tower costs between $1 million to $5 million to build and between $250 000 and $500 000 yearly to operate and maintain. NASA estimates it would cost $100 000 to install an APAS and that it would require little maintenance. Test results were quite favorable though there are still bugs to be worked out. After detecting an aircraft on radar, APAS has a 7- to 20-second delay before it calls that aircraft as traffic. In that time, the aircraft may have changed course. It cannot keep up with fast-moving jets and twins and there are problems with radar ground clutter. The radar also can pick up ground vehicles and mistake them for aircraft. However, NASA has found APAS to be 95 to 98 percent accurate, and elevating the radar a little can eliminate the clutter and confusion to a large extent. The door is open to begin engineering a line unit should funding be available.

Digital Electronics

The revolution in digital electronics has dramatically affected the design and capabilities of emerging avionics systems because of the spectacular reduction in cost, size, and power required of digital electronic components. System cost has decreased sharply with the transition from analog to digital hardware. Data sensing, data processing, and data transfer have now been impressively enhanced and refined, all with reduced weight and number of connectors.

Digital fly-by-wire control systems, using electromechanical actuators in lieu of hydraulic actuators, are a reality in military aircraft with applications for large transports and eventually GA aircraft. The advanced avionic or "all-electric" airplane is a very real possibility for the future of GA.

NASA has been studying GA digital optimal control autopilot designs. A joint NASA, Information and Control Systems, and Princeton University program designed and flight tested a multimode digital autopilot in the Navion. Heading command, altitude command, pitch/roll attitude command, and an Instrument Landing System (ILS) coupler mode autopilot were tested with overall good performance.

Controls

Controls were also investigated under the SPIFR program. The University of Kansas assessed various nonconventional GA manual control devices. The study found that the conventional yoke is not the best aircraft control arrangement when considering the pilot work load requirements of IFR flight. A side stick controller emerged as the best configuration, having better two-axis integration of control inputs, fewer inadvertent inputs, increased instrument panel visibility, decreased pilot work load, and favorable control characteristics in general. Simulation and flight tests remain to be conducted to verify the findings.

Displays

Use of conventional primary displays in instrument landing approaches has been studied both analytically and in the simulator.

Pilots flying the simulator tended to "chase the needles" or overcontrol as they got closer to touchdown, from 5 nautical miles out to 1.25 miles. During nonprecision instrument approaches (those without glideslope or vertical descent needles), conventional displays tended to be disorienting, causing high pilot work load. The development of cathode ray tube (CRT) and microprocessor technology has made it possible to consider combining many sensor signals in one display. Improved performance and reduced pilot work load are definite possibilities.

Advanced symbology for GA terminal area displays was evaluated in flight tests using the Navion and the Wallops tracking radar. The display symbology was that previously used in NASA's terminal configured vehicle program for commercial airlines, including such areas as vehicle track-angle, flight-path angle, and a perspective representation of the runway. The question is whether or not this type of symbology, which takes up a significant amount of space on an airliner's instrument panel, can be fitted into the smaller GA aircraft panel. To investigate this, the advanced symbols were selectively drawn on a CRT display along with the roll/pitch attitude and ILS localizer/glideslope deviation. In general, the symbology in both advanced displays permitted more precise and consistent tracking of the ILS localizer and glideslope signals than did the standard hardware display.

Man/Machine Interface

Since modern IFR flying has become extremely demanding, sometimes taxing the pilot's limits due to increased aircraft traffic and more sophisticated and complex ground control systems to handle this traffic, GA users as a whole consider it imperative that all the pilot's sensory and manipulative skills be optimized in managing aircraft systems.

One revolutionary technology that can improve the pilot's interface with these systems is computer-based voice recognition/synthesis. Princeton University tested this voice recognition equipment (VRE) in flight with its research Ryan Navion. A voice recognition module was linked to a digitally tunable VHF Omnidirectional Radio Range (VOR) navigation receiver. After first "training" the module while taxiing out, the pilot tuned the

receiver in flight using brief spoken commands. Approximately 95 percent of the pilot's spoken commands were properly interpreted by the VRE. A second pilot, for which the VRE was not trained, found that approximately 60 percent of the commands were properly interpreted.

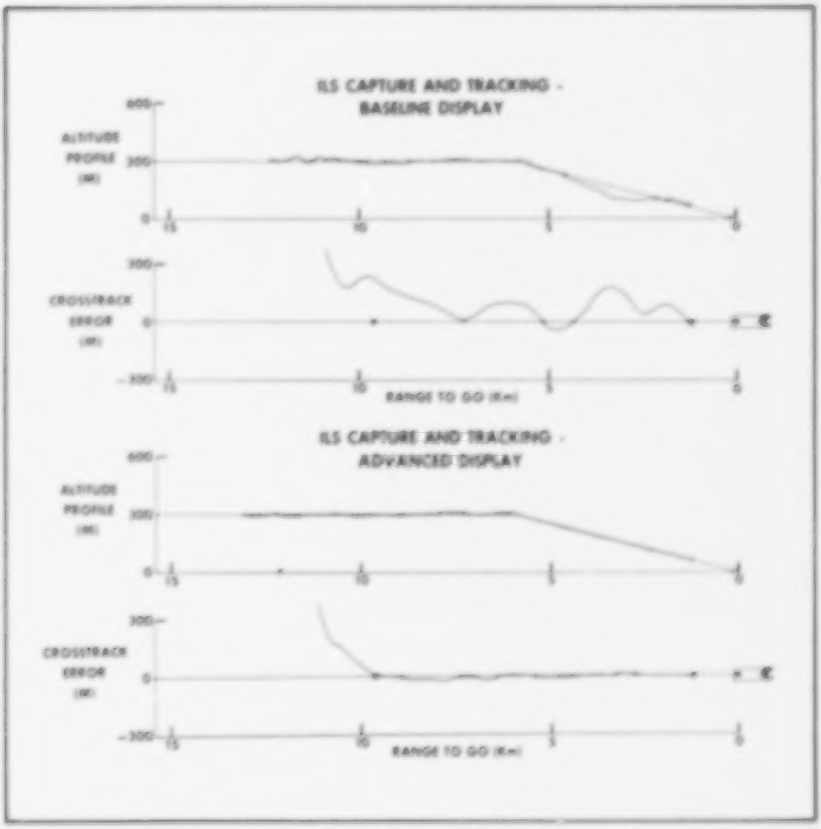
An effort to provide low-cost, timely, efficient weather data to the pilot in flight is ongoing. Ohio State University studied taking digitized weather data generated by a ground-based weather radar and spherics equipment and displaying this information on a CRT in the cockpit. To take this weather data, which starts as a north-up map, and translate and rotate it so that an aircraft-centered, heading-up map can be provided will constitute a heavy burden for the aircraft computer, something OSU has been studying. Mitre Corporation has developed the initial hardware for installation in Langley simulators and the Cessna 402B SPIFR research aircraft. A flight data console (FDC) has been developed with a CRT display and a set of controls for the pilot to send back acknowledgment signals.

Initial results have been very pleasing, since both a weather radar picture and basic weather data have been transmitted into the cockpit from ATC without voice communication. During flight tests in simulated IFR, the FDC "quiet cockpit" met with generally favorable comments from the pilots regarding reduced work load and error-free communications. The only problem concerned the lack of traffic information gained by monitoring ATC communications with other aircraft since the FDC relies solely on the ATC data link.

A continuing effort is under way to evaluate advanced three-dimensional, computer-derived pictorial displays for enroute, terminal area, and final approach guidance. Simulator studies of what used to be called Box in the Sky, now Follow-Me Box, have shown some improvements in SPIFR. This CRT display consists of a three-dimensional box that is located on the desired enroute or instrument approach flight path. The box moves along the path ahead of the aircraft; all the pilot has to do is follow the box. During the approach phase, the box serves as a way point gate, and the pilot must fly through it to maintain proper glideslope and localizer position. Simulator results, which will have to be backed up with actual flight tests in the Cessna 402, have shown that

pilots were able to fly instrument approaches with far less deviation than with the normal instrument landing system.

A flight test study of the system was conducted at Wallops using the Princeton Navion, verifying that the short, curved, descending, precisely controlled landing approach executed in the simulation study also could be performed in flight. Further studies to refine the box are being undertaken for possible installation in the Cessna 402.



Simulator studies were conducted that compared how pilots performed flying a normal instrument landing system (ILS) with directional needles versus how they did flying advanced displays on cathode ray tubes (CRT). As shown, the advanced displays significantly enhanced accuracy.

Demonstration Advanced Avionics System

At the heart of NASA's SPIFR program is the demonstration advanced avionics system (DAAS) installed in the Cessna 402B. The purpose of the project is to define an avionics system for the future that would provide more information at a lower cost and a reduced work load.

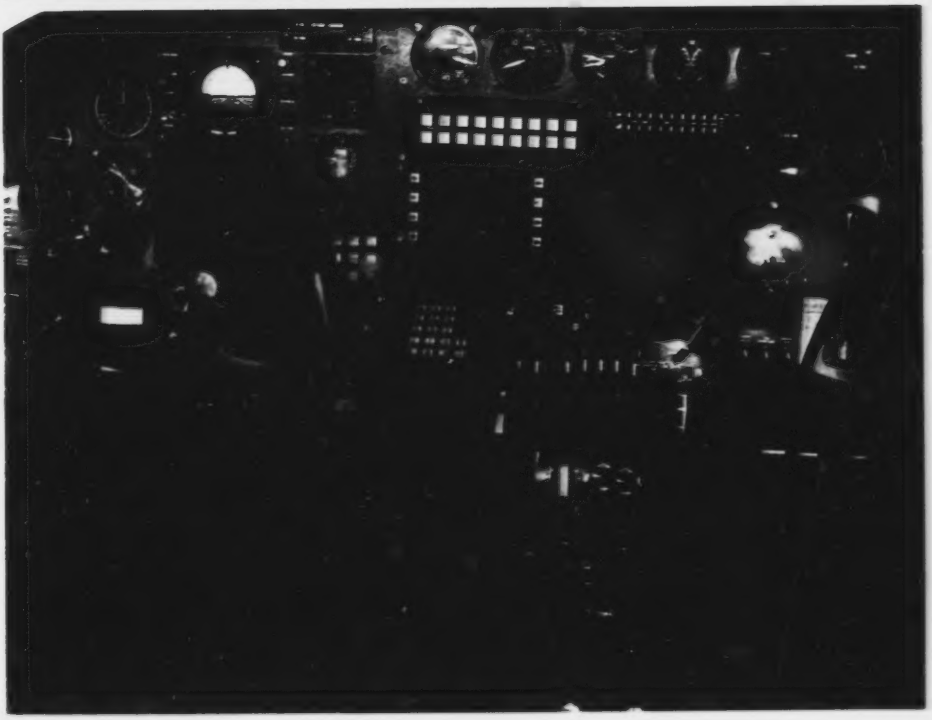
In August 1978 a contract was awarded to Honeywell through Ames, teamed with King Radio, for the design and fabrication of the DAAS, which would: (1) provide information crucial to the design of integrated avionics for GA in the mid-1980's and beyond; (2) use data busing, distributed microprocessors, and shared electronic displays for enhancing reliability and pilot interface; and (3) enhance safety and reduce pilot work load for SPIFR operations. A series of 64 successful demonstration flights was made at Ames, ending in mid-1982.

Many of the features now being incorporated into commercial airliners became a part of the DAAS system, including autopilot/flight director, navigation/flight planning, flight warning, weight and balance computation, Greenwich mean time clock, fuel totalizer, performance computations, air traffic control Mode S or discrete address beacon system message processing, built-in test, checklists and emergency procedures, and ground simulation.

DAAS is built around eight bus-connected microprocessors, seven of which are dedicated to specific functions with the eighth as a spare for two of the others. The integrated data control center (IDCC) is the primary pilot input device through a 10-button keyboard linked to both CRTs and numerous push buttons. In addition to the electronic displays, the DAAS instrument panel includes a conventional attitude director/indicator and airspeed, altimeter, rate of climb, radio magnetic indicator, angle of attack, fuel, and engine instruments.

TOP (Right) The NASA Cessna 402B, stationed first at Ames and then at Langley, has been at the heart of advanced SPIFR research, particularly in connection with the Demonstration Advanced Avionics System (DAAS).

BOTTOM (Right) Here is the DAAS installed in the Cessna 402 with both CRTs lighted and the systems turned on.



Twelve push buttons at the top of the data display control the page format displayed to the pilot, and a switch adjacent to the keyboard permits leafing forward or backward through multipage formats. Warning messages show up automatically on the bottom of the display to indicate the reason for a caution or warning light.

The electronic horizontal situation indicator (EHSI), the CRT directly in front of the pilot, combines the features of a conventional HSI and Jeppesen navigation charts with additional alphanumeric and symbolic navigation data. It portrays the aircraft, way points and navigational aids, and course lines connecting way points in sequence. It also displays a course direction arrow and course deviation dots. The map can be displayed in either a "north-up" or "heading-up" mode. "North-up" is normally used for reviewing a flight plan prior to takeoff or for orientation. "Heading-up," which simulates the view out the windshield, normally is used in flight. Map scales of 2, 8, or 40 nautical miles can be selected by the pilot for approach, cruise, and flight planning, respectively.

A heading scale, digital readout of heading, and heading select "bug" for autopilot or flight director are displayed at the top of the EHSI, and a digital readout of selected heading is at the left below the scale. The left side displays the minimum descent altitude or decision height, active way point, selected course, distance and time to the way point, and way point altitude for use in vertical navigation. A "dead reckoning" or manual navigation mode can take the place of an active way point. The right side of the EHSI displays radar altitudes, availability of the next way point, and a vertical track angle scale.

The bottom of the EHSI has a map scale readout and wind direction arrow with digital velocity readout. The map can be slewed around to view other portions. If a pilot loses the aircraft symbol on the map as a result of excessive slewing, the "map return" push button can bring things back to normal.

The DAAS tests met the program goals and the 60 pilots who flew it generally thought the system was a good step forward in enhancing safety and reducing IFR pilot work load. Half said it was simpler to use than conventional instrumentation but 22 percent said it was more complex. Training and currency on use of the

equipment were deemed mandatory, along with some more human engineering.

Recommendations for more operationally oriented flight tests were made as well as flight evaluations of the Follow-Me Box, ATAS, side arm controller, and other NASA projects. As a result, a second series of operational flight tests was initiated at Langley with attention to the pilot/machine interface, pilot training and work load requirements, and the individual DAAS features. One of the major drawbacks for current development of the system is cost, primarily due to the expensive CRT displays. Should cheaper flatboard hardware be developed, the DAAS could very well lead to a major breakthrough in single-pilot IFR flying.

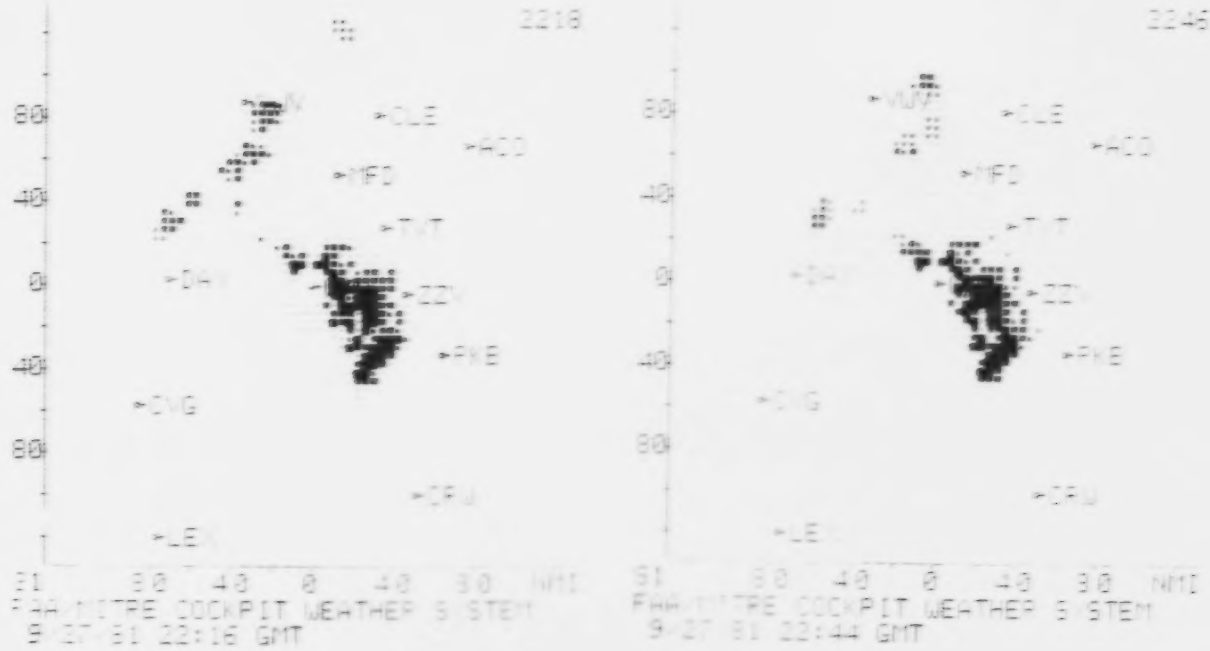
Fluidic Controls and Instruments

Another revolutionary development of the last 10 years has centered around fluidic controls and instruments. Electrofluidic instruments will leave the old gyroscopic instruments behind, which have a tendency to hang up or tumble.

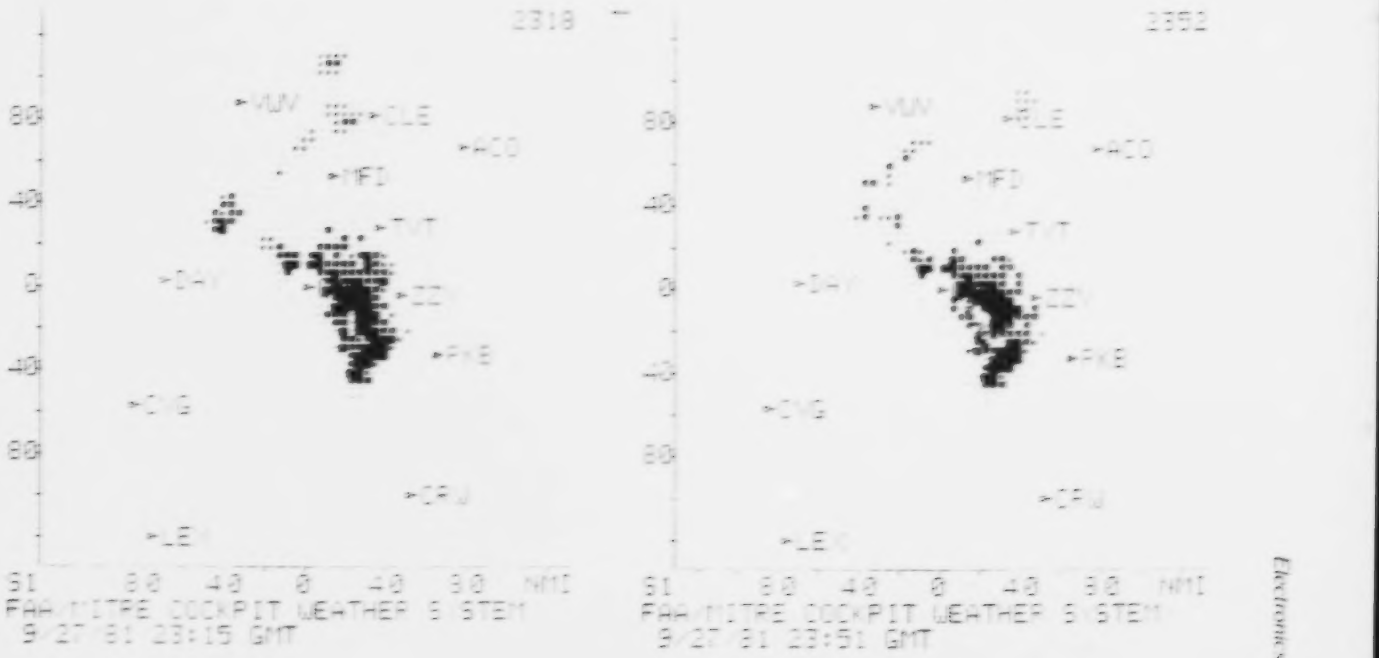
One of NASA's basic objectives in autopilot design was to develop an "aerodynamic aileron," a device for use in autopilot and stabilization systems that could produce torques about the roll axis with no moving parts. An electrofluidic rate sensor package was constructed and calibrated, then sent to the University of Kansas for tests. A laminar jet rate sensor, using ram air only, exhausts air through slots in the wing tips. Lift is increased by displacing wing tip vortex or decreased by disturbing flow pattern, providing proportional control of torque equivalent to 7 degrees of aileron deflection using mechanical switching.

This led to the design of a GA autopilot that uses an electrofluidic wing leveler and heading hold with a highly reliable, low-cost sensor package. Heading reference was provided through a flux gate magnetometer.

A true airspeed sensor was developed as well with no moving parts, designed for low-cost fabrication and easy interface with digital systems. For very little cost this transducer can link up with a dead reckoning moving map to form a very cheap version of an inertial navigation system. Computer programming for the device is simple and state of the art, and microprocessors can be adapted



These printouts from the FAA/Mitre Corporation test equipment show significant weather on a CRT in the form of rain. Obtaining accurate weather information in flight is one of the more serious needs for SPIFR flying. This test equipment has gone a long way toward achieving that goal.



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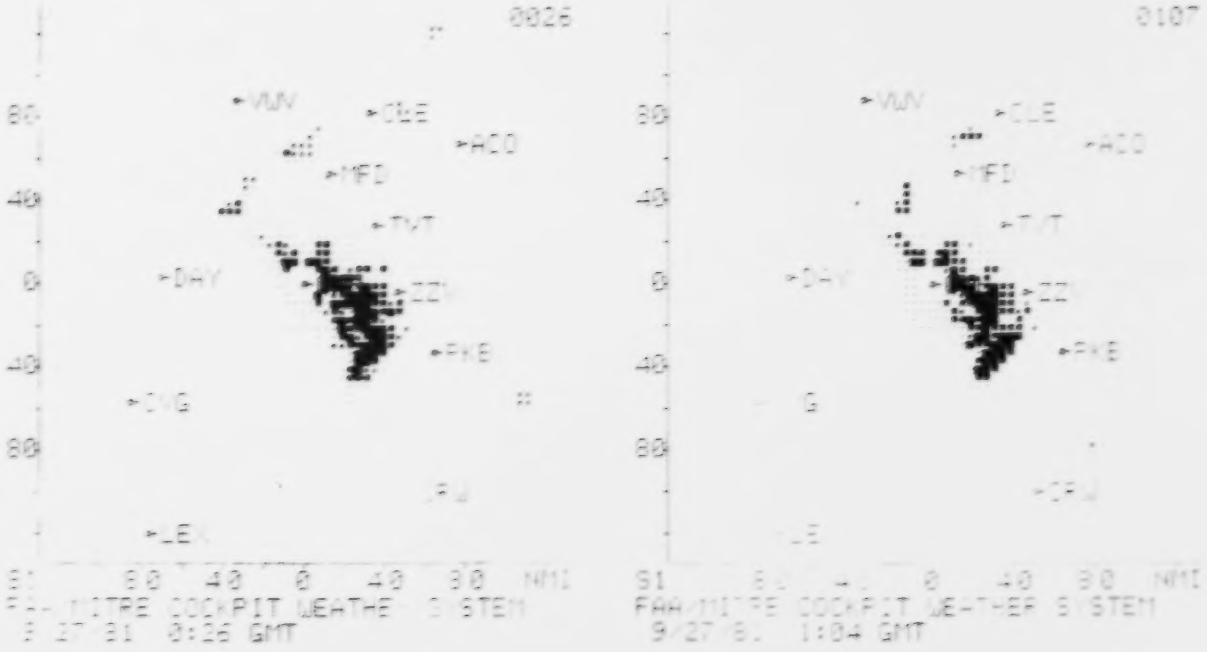

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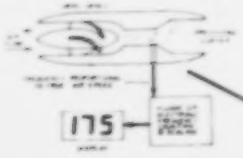
RESEARCH at NASA LANGLEY

FLUIDIC AND ELECTRO-FLUIDIC FLIGHT INSTRUMENTS

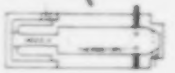
ELECTRO-FLUIDIC NORTHERLY TURNING ERROR COMPENSATOR FOR COMPASS AND AUTOPILOT

MAGNETOMETER HEADING REFERENCE

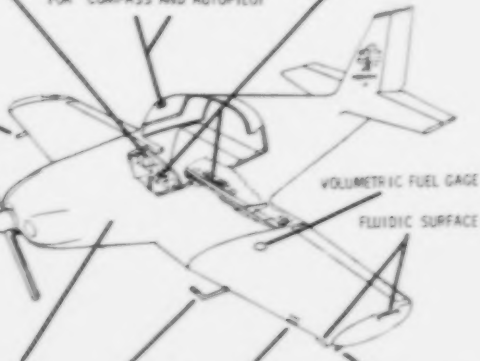
FLUIDIC AND ELECTRO-FLUIDIC WING LEVELERS AND AUTOPILOTS



FLUIDIC TRUE AIRSPEED INDICATOR



LAMINAR JET RATE SENSOR



VOLUMETRIC FUEL GAGE

FLUIDIC SURFACE CONTROLS

FLUIDIC VARIABLE

INTERNAL VENTURI VACUUM SUPPLY

FLUIDIC AUTO-THROTTLE

ANGLE OF ATTACK SENSING AND CONTROL

DIFFERENTIAL WINGTIP VELOCITY SENSING

TOTAL ENERGY PROBE

General aviation fluidics

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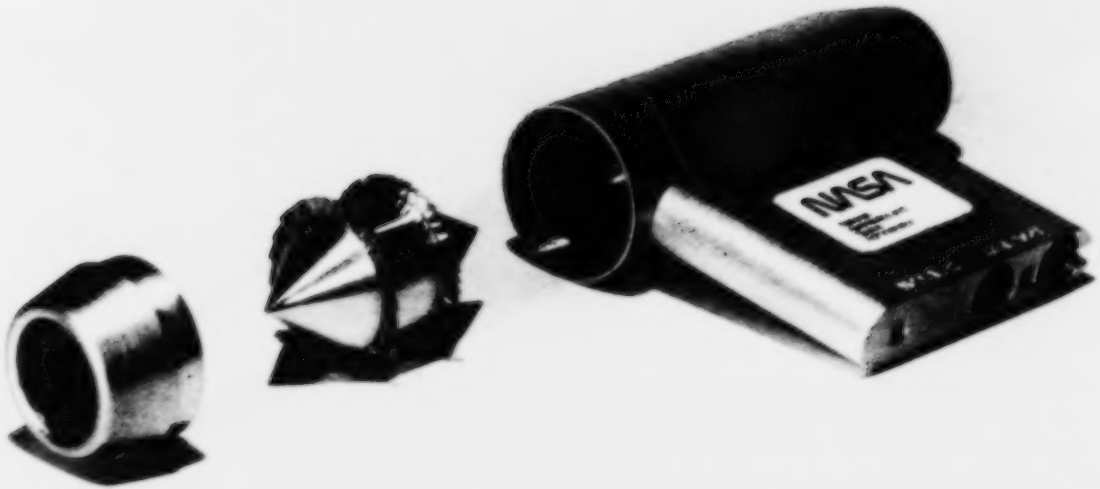

Shown here is the true airspeed sensor disassembled. Clearly evident through all of these fluidic and advanced autopilot controls is simplicity and low cost. Developed, these concepts could prove a breakthrough in better accuracy and ease of operation for less cost, something that has not happened in general aviation for some time.

A true airspeed sensor was developed as well with no moving parts, designed for low-cost fabrication and easy interface with digital systems. For very little cost this transducer can link up with a dead reckoning moving map to form a very cheap version of an inertial navigation system. Computer programming for the device is simple and state of the art, and microprocessors can be adapted to it for future use. The digital autopilot of the future now appears not as complex as once thought.

NASA has been involved in other fluidic studies and concepts as well. A fluidic (Coanda effect) propeller was developed under a NASA contract with Bionetics Corporation. It may take the place of the standard variable pitch propeller. Fixed pitch, circulation-controlled propellers are those in which the necessary propeller aerodynamic changes caused by airplane speed changes could be obtained through changes in blown-jet mass flow rate.

Studies indicated that elliptical and supercritical circulation-controlled airfoils were aerodynamically feasible. The Coanda effect is used by blowing at the trailing edge of the propeller to vary the effective pitch, thus providing propulsion efficiencies comparable to those of conventional variable pitch propellers without the attendant mechanical complexities of the variable pitch hub. When comparing performance on a 1600-kilogram single-engine aircraft in computer studies, the supercritical, circulation-controlled prop with a single blowing plenum was equal to standard propellers at high-speed cruise. At low speed, the Coanda effect prop exhibited a performance gain over a fixed pitch but lost performance when compared with a variable pitch type. More studies will have to be conducted to see if it will be economical to replace currently manufactured propellers with this revolutionary new design.

The meteoric improvements being made in electronics and avionics are finding their way into general aviation. Potential for increasing safety, utility, and comfort is wide open when coupled with the capability to make sophisticated equipment affordable to industry and ultimately to GA users.

CHAPTER 9

THE FUTURE

The early 1980's were certainly years of contrast for general aviation. The recession grounded aircraft and production lines were either slowed down or shut down entirely. To visit Cessna, Beech, Piper, Mooney, or any of the other manufacturers was quite a sobering experience, miles of half-completed aircraft silent in darkened and still buildings.

According to many, those years were the worse since the 1973–75 recession. In the first 10 months of 1981 new aircraft sales fell 46 percent to 571. The single strongest sector of GA production involved new turboprops and corporate jets, although these lines were certainly slowed down. In spite of the slowdown, general aviation remains vigorously active.

NASA and its forerunner NACA have been central to keeping the United States in the forefront of aeronautics. Long before there was a "space agency," NACA became a partner of the aviation community in bringing the U.S. to a position of world leadership in aviation. There are many reasons for this success. First, the government's investment provides for the development and operation of major aeronautical ground and flight test equipment, which not even the largest of private companies could afford. Second, NACA was governed by a committee with membership from government, industry, and university sectors of the aviation community. NASA continues to maintain a strong Aeronautics Advisory Committee with similar representation, including programs designed to ensure responsiveness to community needs. Third,

NASA has no regulatory authority. It exists solely to serve its customers: the Department of Defense; Federal Aviation Administration; thousands of private companies that build aircraft, engines, parts, and subsystems and that operate and service aircraft; and the universities that produce many skilled aeronautical scientists and engineers.

Aeronautics remains vital to the U.S. economy. Civil aircraft sales have grown more than eight times that of the overall gross national product. The export portion of these sales has become a major favorable component of the country's trade balance. The ailing economy of the 1980's has forced the GA industry to slow down, opening the door to foreign competition as never before. NASA's help is more vital than ever in preventing this key segment of the U.S. balance of trade from deteriorating. It is interesting to note that the total sum expended on aeronautical research, facilities, and personnel by NASA and NACA over their combined 68 years of existence amounts to less than half the dollar value of U.S. aeronautical exports in 1979 alone.

The U.S. enjoyed a clear and impressive leadership position in free world competition for the total $87 billion in civil aircraft sales during the 1970's. For the much larger market of the 1980's and 1990's this leadership is by no means assured. Foreign manufacturers have concentrated effective efforts on the design and production of highly competitive air transports, commuter aircraft, and helicopters. European and South American competition, along with developing capability in Japan, are already producing the technically equal or superior article to U.S. products. NASA remains a vital $4 billion national asset to keeping U.S. aeronautics in the forefront.

Based on the government subsidies available to foreign aircraft companies, U.S. manufacturers have asked for increased participation by NASA, particularly in general aviation and rotorcraft since research facilities are so limited.

Though much of the U.S. is still a free market internally, aircraft are in an international environment where success may depend on markets outside the U.S. and even outside Western Europe. The bottom line for the U.S. is unquestioned excellence at low manufacturing costs, a challenging combination.

General aviation remains vital to American business since 80

percent of current and projected GA markets are for business and commercial applications. General aviation is the only mode of air travel available to many businesses and small communities, a situation aggravated by airline deregulation. Future growth projections for general aviation and commuter aviation total $80 to $90 billion through the end of the century.

Despite this attractive potential, there are several serious concerns such as rising costs of operation, particularly due to rising fuel costs, which reduce the utility and therefore the potential GA market. Avgas is being slowly dropped from production, leading to rising cost and lack of availability. Energy efficiency and multifuel capability remain major areas of research.

In recent years, commuter airlines have had to buy foreign aircraft because suitable U.S.-built products were not available. Foreign competition in the higher performance turboprop and turbofan business aircraft has increased significantly. Safety will remain in the forefront of research since accidents will have to be reduced to increase use of GA aircraft. When accidents do occur, serious injuries and death will have to be minimized.

General aviation's future, though bright, may not involve the U.S. as it has in the past if NASA's research efforts are not bolstered. According to those companies involved with NASA, they would like more government involvement. As one GA company president said, "We are now at the point where we will work with NASA on a day-to-day basis in certain specialized areas. What this means is that aircraft manufacturers of our size whose potential for basic and applied research, though improved, is still limited. Our future success in world markets, which we have dominated until now, will quite literally and directly depend on the success of NASA in performing the basic advanced aeronautical research which the agency and the industry can and should do together."

In general, GA companies do not believe that NASA's role is to develop actual aircraft hardware, but rather to concentrate on advanced concepts that industry can apply to its product. Since recent U.S. research and development efforts have lagged behind those of other nations, once firm economic leads are evaporating. Not too long ago there were six U.S. manufacturers building business jets, an American innovation on the whole, with the

foreign competition coming from the aircraft industries of France, Germany, and England. Today there are only three U.S. manufacturers building "bizjets," and they now face competition from companies in Canada, England, France, Israel, and Japan, all either owned or heavily subsidized by their respective governments.

The United States is now entering a critical period in its economic history. If research and technology in aeronautics continue to be deemphasized, while at the same time deemphasizing research and technology in agriculture, the U.S. will be undercutting the two areas that contribute most to the nation's balance of payments. As the GA manufacturer continued in commenting on NASA's help and research, "It is almost inconceivable to me that we would be taking steps that literally kill the goose that lay the golden eggs in the economy of this country, and we are talking about extraordinarily small amounts of money to keep that goose not only alive but fat and laying very well."

NASA remains a vital link in America's aeronautical leadership. Nowhere is that more evident than in general aviation where companies depend on NASA to develop products that will compete in the world marketplace.

ABOUT THE AUTHOR

Jeffrey L. Ethell, a certified flight instructor and commercial pilot, is author of more than 24 aviation books and a well known free-lance writer for numerous aviation magazines, including *Air Force Magazine, Air Progress, Air Classics, Aerospace America,* and *Popular Mechanics.* He is a member of the American Aviation Historical Society and the Warbirds Division of the Experimental Aircraft Association. In addition to being an experienced pilot of such World War II aircraft as the P-51 Mustang and the B-25 Mitchell, Ethell has logged several hundred hours in modern military jet aircraft.